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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

TECHNICAL NOTE No: MECH. ENG. 209

THE USE OF FUEL FOR COOLING PURPOSES IN AIRCRAFT

by

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The use of fuel for cooling purposes in aircraft

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SUMMARY

The cooling potential of fuel consumed by the propulsion engines of an aircraft depends on the fuel flow, the initial fuel temperature and the maximum fuel temperature permissible in any part of the system. The latter limitation is taken to be imposed by the necessity to prevent vapourisation in the fuel system or over-heating its components.

Only a portion of the available potential can be usefully employed for space or equipment cooling due to the effects on the fuel of inefficient pumping, aerodynamic heating and heat flow from the engine installation.

It is concluded that with kerosine or less volatile fuels it is possible to absorb the whole of the internal waste heat loads of currently conceived turbo-jet engined aircraft at speeds up to M = 3.

With volatile fuels such as wide cut gasoline this possibility is marginal, being dependent on the temperature rise of the fuel in the burners on which information is incomplete.

Attention is directed to certain inefficiencies that materially reduce the effective heat capacity of the fuel, and recommendations are made for further work.

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1 Introduction

As aircraft flight speeds increase, the temperature of the ram air rises to values which progressively reduce its utility as a cooling medium. Current operating temperatures are:-

TABLE I

Current maximum operating temperatures

Service or component	Temperature °C
Cabin air	30
Electronic apparatus	55 - 70
Lubricating oil to engine	100
Electrical equipment	120 - 150
Components made of aluminium alloys	100 - 150

The limiting Mach numbers for direct ram air cooling can be seen in Fig.1, and also those for air at ram temperature cooled in a simple turbine of 6:1 expansion ratio. Other methods, such as cascade expansion of air or evaporation of a liquid may be used, but in any case the aircraft fuel is a readily available coolant for some purposes.

In this note an assessment is made of the rise in fuel temperatures in various fuel systems* and the maximum temperatures that can be tolerated. From this and the fuel consumption rate the amount of waste heat that can be absorbed by currently used fuels en route to turbo jet engine combustion chambers is deduced.

2 Conditions affecting the cooling potential of the fuel

The possibility of direct fuel cooling depends on:

(i) the fuel temperature being sufficiently low,

(ii) the heat added not causing

(a) fuel vapourisation or chemical instability in a region where this could upset combustion or control e.g. in a pump or metering device,

(b) fuel temperatures in excess of the spontaneous ignition temperature, thus increasing the fire hazard due to leaks, and

(iii) the fuel temperature in any region of the fuel system not exceeding the maximum operating temperature of the system in that region.

As an example of (i), the fact that the temperature of the fuel in the tanks may rise to 50°C while the aircraft is standing on the ground in the

*The term fuel system as used in this note includes all components used for the storage, transfer, pumping and control of the fuel regardless of whether they are mounted on the airframe or the engine. Outlines of two typical turbojet engine fuel systems are given in Fig.2.

sun[1] means that it can not be used directly for cooling the cabin air or possibly the electronic apparatus.

2.1 Fuel temperature limitations

The onset of fuel vapourisation is dependent on the pressure, temperature and the type of fuel. The variation of vapour pressure with temperature is shown for several fuels in Fig.3 (Fig.3 of Ref.6). It can be seen that wide cut gasoline, being more volatile than kerosine, has lower maximum operating temperatures for the same pressures.

The permissible temperatures, and hence the amount of heat which can be absorbed by the fuel en route to the engines, are at their lowest values at high altitude, particularly at engine idling conditions, when the pressures throughout the fuel system are low due to the low ambient pressure and the reduced rate of fuel flow. The following table gives typical values:

TABLE II

Fuel vapourisation limits at 50,000 ft

	Region of fuel system	Minimum fuel pressure p.s.i.a.	Maximum allowable temp. °C		
			Wide cut gasoline	Kerosine	Diesel oil
	Low pressure side of system				
A	Unpressurised fuel tanks	1.68	21	89	145
B	Pressurised fuel tanks	5	52	123	185
C	Main engine pump entry	12	80	162	228
		20	98	198	>250
	High pressure side of Duplex burner system				
D	Main burner lines (max continuous)	30	110	210	>250
E	" " " (idling)	8	65	141	205
F	Pilot burner lines (idling)	50	133	242	>250
G	Before pressurising valve	100	175	>250	>250
	Spill controlled burner				
H	Spill lines (max continuous)	300	>250	>250	>250
J	" " (idling)	100	232	>250	>250
K	Spilled fuel at entry to supply pump. Low booster pump pressure	12	80	162	228
	High " " "	20	98	198	>250
	Vapour burner				
L	Final orifice (max continuous)	10	75	152	219

Temperatures above 250°C should not be exceeded since spontaneous ignition and cracking of these fuels are then liable to occur. Gumming commences in some fuels at a temperature of 110°C but this is avoidable by selection of the fuel.

2.2 Choice of the relevant fuel temperature limitations

The locations where heat may be transferred to the fuel are discussed in section 3, but the maximum temperatures to which the fuel can be raised before vapourisation occurs can be seen from the above table. It must be borne in mind that a high permissible temperature in the early part of the system is of no utility if hot fuel then flows through a lower pressure region where vapourisation may occur. In a duplex burner system the final limitation is given by condition E in the main burner line at high altitude idling conditions. If vapourisation in this region really is the limiting condition it means that there is little cooling capacity available with this system when using wide cut gasoline unless precooling is carried out. A doubt as to whether this is the limiting condition arises from the fact that although vapour emission is known to be troublesome if it occurs at entry to a pump or flow metering device, it is not clear whether this applies in the lines delivering a metered flow of fuel to the burners.

In the case of the spill controlled system with no circulating pump, the limitation is that given by condition K, at entry to the supply pump, since a large proportion of the spilled fuel is passed back to this region at low burner flows.

However, in both these cases it may be possible to take advantage of the higher temperatures which can be tolerated in higher pressure regions of the system under idling conditions if the fuel is then cooled before its pressure is reduced. It appears feasible to accomplish this by a ram air heat exchanger which is brought into use when at the low aircraft speeds associated with low fuel flows.

The use of a heat exchanger in this way also makes possible continued cooling of equipment by the same basic method after exhausting the aircraft's fuel supplies. In this case, operation continues in a closed circuit with no flow to the engines by reserving enough fuel to keep the circuit filled.

Another method of limiting the temperature rise under idling conditions is to pass fuel, additional to that flowing to the engines, through some of the components, and then return this excess to the tank. This technique, either in conjunction with a ram air heat exchanger or separately, is considered to be acceptable for the brief periods when it is likely to be used, particularly if fuel in the low pressure booster circuit only is recirculated. As a result, the fuel in the tanks is heated at the rate of about 10-12°C per hour when sufficient fuel for one hour's high altitude cruise remains. A tank temperature rise greater than about 5°C from this cause is extremely unlikely.

Having regard for these methods of disposing of waste heat when the engine is idling at high altitudes, the most important condition requiring examination is maximum continuous high altitude operation, where the maximum permissible temperatures are given by condition D for a duplex system and by condition K for a spill controlled system. At these conditions, and with speeds exceeding $M = 1.6$ to 1.8 in the stratosphere, the temperature of the ram air is too high to enable it to be used for fuel cooling. Any ram air heat exchanger is therefore bypassed, and the increased engine fuel flow must absorb the heat input into the fuel system without excessive fuel temperature rise.

The low fuel pressures at present employed in vapourising fuel systems appear to eliminate their employment for heat absorption, but there seems to be no reason why the pressure level should not be raised to that of either of the other two systems examined here.

2.3 Fuel system component temperature limitations

The principal temperature limitations are due to the use of rubber in various applications such as flexible bag tanks and for seals in integral tanks, pumps and controllers, and also due to bearing materials and differential expansion in the controllers.

The maximum temperature to which fuel resisting rubber may be subjected depends on the useful life required and whether it is exposed to air or not. Typical values are:-

TABLE III

Life of fuel resisting rubber at elevated temperatures

Temperature °C	Surrounding Medium	Life-Hours
130°C	Air	150
"	Oil	600
150°C	Air	24
"	Oil	350

There is apparently no immediate prospect of an increase in these temperatures.

In a number of cases it is possible to replace rubber by other materials e.g. flexible pipe may be constructed of metal, and its complete elimination from the fuel system should not be impossible.

At moderate stresses, bearing materials should be able to operate at a temperature of 200°C, and the present day limitations of 100°C for pumps and 70°C for controllers are often associated with differential expansion difficulties.

3 Location of heat transfer to the fuel

Heat transfer to the fuel can be arranged to take place in three locations, either separately or in conjunction with one another:-

A By mounting a heat exchanger in a fuel tank, or by passing fuel from the fuel tank, independently of the engine flow, through a heat exchanger back to the tank.

B During transfer of the fuel from the tank to the main engine pump.

C On the high pressure side of the main engine fuel pump.

The first method enables the flow to be adjusted to suit the cooling demand and initially uses the coldest fuel available in the system. The temperature rises however at an increasing rate as the tank empties, and the heated fuel is subsequently passed through all the fuel system components. In addition the pressure level is low, and the fuel temperature rise must be limited to a greater extent than with the other locations to prevent boiling.

Method B uses practically the coldest fuel available (since the heat input from the tank pumps is small) and does not raise the tank temperature, but the flow is dependent on the main engine demand and will vary greatly at

different speeds and altitudes so that loads which persist when the engine flow is low may not be covered adequately unless a bypass back to the tank is employed. In many cases the change in the heating loads at high altitude or throttle back conditions does not match the reduced fuel flow. The vapourisation limit is higher than in the former case since the pressure is increased by tank pumps in most cases.

Method C is used at present for oil cooling on some engines, and allows the fuel to be raised to the highest possible temperature, particularly if the heat exchanger is placed after the flow controllers. However, this is the point in the system where fuel temperatures are already high, thus limiting the cooling applications. Another disadvantage is that it involves mounting further heat exchangers on the engine, or taking metered fuel away from the engine to a remote heat exchanger and back again. These difficulties should not be too great if consideration is given to them at the design stage. Troubles due to flow variation will again be encountered, and the technique of bypassing additional fuel back to a lower pressure region is not as attractive as in case B since the higher pressure results in greater fuel heating due to pumping inefficiency.

The difference between the limiting temperatures based on vapourisation in the three locations (Table II) and the tank temperature is a measure of the quantity of heat which can be absorbed by the fuel prior to each location. For a tank temperature of 50°C it can be seen that the capacity available using method A, with a permissible temperature rise of only 2°C for wide cut gasoline, is small, and that methods B and C give promise of considerably greater cooling capacity.

However, quite a large proportion of this cooling capacity is today being utilised in various ways, and this aspect is considered in the next section.

4 Heat input to the fuel on current aircraft

The sources of fuel heating on current aircraft are associated solely with operation of the engines, and arise from inefficient fuel pumping, pressure reduction by throttling, cooling of the lubricating oil and heat transfer from the combustion zone to the fuel burners. Full discussion of these matters is relegated to Appendices I and II, and a summary only is given here.

The power taken by the booster pumps in the fuel tanks of a present day four engined bomber is about 5 KW, and at an assumed efficiency of 25% this results in a 1°C temperature rise of the fuel at the flow demanded at high altitude cruise. This temperature rise is taken to apply in all cases considered.

The power taken by the main engine pump of a typical 10,000 lb thrust engine may amount to 25 HP and the reheat pump for such an engine may take about 50 HP. Some fuel heating is bound to occur due to pumping inefficiency but the magnitude of this effect depends on the type of pump and the arrangement of the fuel system.

The method of obtaining burner flows lower than the pump maximum output is most important, because the fuel flow range of a turbo-jet engine between sea level and high altitude maximum power conditions is about 10:1 without taking into account the use of reheat or the fact that the pump output may be appreciably greater than the maximum fuel demand.

In Appendix I is shown the considerable reduction of fuel heating at high altitude obtained by using a variable displacement instead of a constant

displacement pump. Fig.9 illustrates the fuel temperature rises which may be obtained with various systems.

An engine driven reserve or reheat pump can result in a considerable rate of fuel heating when its output is being largely or entirely bypassed. This is indicated in Fig.10. An independently driven pump, which can be stopped when not required, is a far better arrangement where the output is only required for a brief part of the flight period.

Fuel cooling of the engine lubricating oil is now becoming general, and can result in an appreciable temperature rise of the fuel as shown in Appendix II and Fig.11.

In both spill and duplex burners heat is transferred from the combustion gases to the fuel in the burners and the burner lines. The effect of this in raising fuel temperature is taken into account to a large extent in the case of the spill burner by using the measured values given in Fig.12 for the temperature rise of the fuel spilled to the pump inlet, but the effect of such heating in giving rise to vapourisation in the burner swirl chamber and the sensitivity of the burners to vapourisation in this region require more investigation. Various measures such as insulation or shielding may be adopted to reduce heat transfer in this region.

The temperature rises of the fuel en route to the engine due to these effects are tabulated below for two types of fuel system using engine driven pumps at a fuel flow of 10% of the maximum rate, which approximates to cruise conditions at 50,000 ft.

TABLE IV

Total fuel temperature rise in current engines

Cause of fuel heating	Temperature rise at high altitude °C	
	1 Duplex burner system with variable stroke pump	2 Spill burner with constant stroke pump
Booster pumps in tanks	1	1
Engine oil cooler:		
Single shaft engine	10 - 23	10 - 23
Two shaft engine	35	35
Pumping inefficiency	5	21
Heat transfer to burner	not known	16
Total fuel temperature rise:		
Single shaft engine	16 - 29	48 - 61
Two shaft engine	41	73

The use of a constant displacement engine driven reheat or reserve fuel pump will, in addition, raise the main engine pump inlet temperature very considerably and can also result in heating of the fuel in the tank at a rate indicated by Fig.10.

The values given above are dependent on the specific heat of the fuel (which will not differ appreciably for any fuel of the petroleum type), on the

pump delivery pressure and on the proportion of the maximum pump output which is used at high altitude.

It can be seen from the above table that a single shaft engine results in less fuel heating than one with two shafts, and that fuel system (1) gives 32°C less temperature rise than system (2). This difference will however be affected by heat input to the burners themselves if vapourisation in this region is critical. Lack of knowledge on this matter makes a full comparison of the two systems impossible.

5 Heat input to the fuel in future aircraft

The fuel temperature rise due to inefficient pumping and oil cooling is taken to be the same in future high speed aircraft as given in Table IV on the basis that fuel pressures and pump efficiencies will not change appreciably from present day values, and that improved bearing cooling and insulation techniques will keep pace with increasing compression and combustion temperatures.

With increasing flight speeds however, further heat quantities will be passed into the fuel as the result of aerodynamic heating, and thus reduce its capacity to absorb the aircraft's internal waste heat loads.

5.1 Aerodynamic heating of the fuel in high speed flight.

The extent of aerodynamic heating of the fuel depends on the aircraft speed and the shape and the degree of insulation of the tanks and pipe runs either by virtue of their location or wall construction - the heating effect being less, for example, in fuselage tanks than in those located in the wings. The degree of insulation required depends on how the aircraft is used, since if there is a period of subsonic high altitude flight prior to a short supersonic period it can be advantageous not to insulate so as to obtain some degree of fuel cooling. Drop tanks which are either discarded or emptied prior to supersonic flight are useful in this respect.

The extent of aerodynamic heating of the fuel is estimated in this note for uninsulated and insulated tanks in which either the submerged surface only or the entire tank wall is cooled by the fuel when the tank is partly full.

In the uninsulated case the heat transfer is calculated from Ref.4 using the following relationship:-

$$q = 2.00\, Re^{-1/5} \left(\frac{T_1}{T_\omega}\right)^{0.46} \rho.u.C_p\, (T_{\omega_0} - T_\omega)\ \text{C.H.U./ft}^2\text{/min}$$

where Re = Reynolds number = $\frac{\rho u x}{\mu}$

ρ = density of air lb/ft^3

u = velocity ft/sec

x = length of fuselage or wing ahead of the tank centre - ft

C_p = specific heat of air

T_1 = ambient temperature °K

T_ω = surface external temperature °K

T_{ω_0} = surface external temperature for zero heat transfer °K

The wall external temperature T_ω is assumed equal to the fuel temperature T_f, and the rate of fuel temperature rise is then

$$\Delta T_f = \frac{q\,S}{\rho_f \cdot V_f \cdot C_{p_f}}$$

$$= \frac{2.00\,Re^{-1/5}\left(\frac{T_1}{T_f}\right)^{0.46} \rho \cdot u \cdot C_p\,(T_{\omega_o} - T_f)\,S}{\rho_f \cdot C_{p_f} \cdot V_f} \qquad (1)$$

where S = tank surface area through which heat transfer occurs - ft^2

ρ_f = fuel density = 50 lb/ft^3 for petroleum type fuels

V_f = fuel volume - ft^3

C_{p_f} = fuel specific heat.

In the case of insulated tanks, a 1" thickness of glass wool, thermal conductivity $K = 0.3$ $CHU/hr/ft^2/inch/^oC$ has been assumed. The wall external temperature T_ω is taken equal to T_{ω_o}.

Then heat transfer

$$q = \frac{0.3}{60}(T_{\omega_o} - T_f)\,S \qquad CHU/min$$

and

$$\Delta T_f = \frac{0.005\,(T_{\omega_o} - T_f)\,S}{\rho_f \cdot V_f \cdot C_{p_f}} \qquad {}^oC/min \qquad (2)$$

Equations (1) and (2) have been applied to fuel tanks in aircraft flying at 50,000 ft. Fig.13 shows the rate of fuel temperature rise at various fuel temperatures for unit value of S/V_f for uninsulated tanks, and Fig.14 gives the rate for unit value of S/V_f for insulated tanks. The ratio S/V_f of surface area through which heat transfer takes place to the fuel volume is plotted in Fig.15 for cylindrical and slab tanks containing varying fuel quantities for the case where heat transfer occurs through the entire area exposed to the external air stream as a result of spray cooling the dry wall, and for the case where heat transfer only occurs through the surface submerged by fuel.

As an example of the fuel temperatures attained due to aerodynamic heating, particular cases have been evaluated and the results are plotted in Figs.16 and 17 for uninsulated tanks and Figs.18 and 19 for insulated ones. Thorough mixing is assumed to take place inside the tank, otherwise the fuel temperature at the wall will be considerably greater than that at the centre.

It can be seen that at Mach numbers above about 2 the fuel temperature rises rapidly particularly in uninsulated wing tanks or if the entire tank surface is cooled by the fuel.

Consideration is given to the latter case because, as shown in Ref.5, the temperature of the dry tank wall above the fuel level can rise to high values during sustained flight even when insulation is used. The resulting wall temperature may be undesirable from the point of view of exceeding skin or sealing material temperature limitations, thermal stress, or the possibility of attaining the fuel spontaneous ignition temperature.

The heat capacity of the fuel can be most efficiently utilised for wall cooling as suggested in Ref.6 by passing the flow around the fuel tank en route to the engines, thus shielding the bulk of the fuel from heating effects. This gives a fuel temperature rise which is independent of the time of flight and is estimated at the following values for a 200,000 lb A.U.W. aircraft similar to that taken in Ref.6, having a tank surface area of 1,300 ft^2 insulated by a 1" layer of glass wool.

TABLE V

Aerodynamic heating of the engine fuel flow consequent on shielding insulated fuel tanks

Mach Number	1.5	2	2.5	3
Fuel Temperature rise ^oC	0	0.8	1.8	2.6

If it is assumed that the fuel pressure in the shielding passages is that at the engine pump entry, the fuel temperature attained will be well below the limiting temperature of 80^o for wide cut gasoline.

5.2 Absorption of the waste heat from the auxiliary equipment

Heat is generated inside the aircraft by the electrical and hydraulic systems, and cooling is required for the cabin air. The magnitude of these heat loads depends mainly on the magnitude and efficiency of power generation and utilisation which vary with aircraft size, type and Mach number, and can not be defined generally. Increasing functional and strategic capacity with the passage of time appears to be a very important factor contributing to increasing these loads in future aircraft.

The assessment of the temperature rise of the fuel flowing to the engines consequent on absorbing the aircraft internal waste heat loads is therefore carried out for several arbitrary values of waste heat per unit all up weight (watts/lb). The temperature rise depends on this value and the fuel flow variation per unit all up weight. The latter variation is derived from the theoretical lift/drag and specific fuel consumption values of Fig.20A for aircraft having the optimum performance at each speed, and is plotted in Fig.20B. The resulting temperature rises are plotted in Fig.21.

For a given fuel temperature rise the value of waste heat capacity per unit all up weight increases with Mach number due to the greater fuel flow at high speeds. From the previous assessments of maximum permissible fuel temperatures and the temperature rises due to pumping, oil cooling and aerodynamic heating loads etc. it is possible to assess the amount of waste heat that can be accepted from the auxiliary equipment.

The cabin air and transparency heat loads are fairly small and, using the values given in Ref.6, will together give a temperature rise of the fuel flow less than 1°C at M = 3.

5.3 Heat capacity available for absorbing internal waste heat loads

In Fig.22 a summation is given of the temperature rises of the fuel flowing to the engines due to the various causes enumerated in this note. An initial tank temperature of 50°C and heating up to the limitations quoted for wide cut gasoline in Table II are assumed. The aerodynamic heating effect included is that encountered due to shielding an insulated tank by the fuel flow. In an unshielded tank, where the fuel in the tank is heated directly, it is assumed that precooling of the fuel is applied so that its temperature in the tank does not exceed 50°C during the whole flight. In this case the aerodynamic temperature rise shown in the diagram should be omitted. A reheat system is presumed to be arranged so as not to result in heating of the fuel when reheat is inoperative.

The residue of the permissible temperature rise after absorbing the aerodynamic, cabin, pumping, oil cooling and burner heat loads is available for the absorption of the auxiliary equipment heat loads.

In Fig.22 a spill controlled burner system using an engine driven constant displacement pump is compared with a duplex burner system using a variable displacement pump from the point of view of utilisation of the fuel as a coolant. When using wide cut gasoline at an initial temperature of 50°C, the spill system is already running into overheating trouble due to throttling losses in the recirculated flow and to heat picked up in the burners.

Under the same conditions a duplex burner system has the margin given in Fig.23 available for cooling purposes plus fuel temperature rise in the burners. The latter value is not known, and since it may be of the same order as the margin available, the use of wide cut gasoline as a coolant can not be advocated for this system until further work has been done to establish the importance and the magnitude of the burner heating effect.

Fig.24 shows the temperature rise available for absorbing the burner and auxiliary equipment heat loads in a duplex burner system and the auxiliary equipment heat loads only in a spill controlled system when using kerosine.

In this case the available temperature rise is large, and the capacity for absorbing waste heat loads in terms of watts/lb all up weight implied by these temperature rises is also plotted on this figure. The values shown for the duplex burner system will be reduced as a result of heat input to the burners, but it appears that either system has ample capacity for absorbing the waste heat loads at present visualised as coming from the auxiliary equipment. When using this fuel or one of lower vapour pressure the equipment temperature limitations will be met before fuel vapourisation commences.

It is conceivable that aircraft limitations may result in a considerable reduction of flight speed at low altitudes relative to the high altitude value and thus reduce the fuel flow range and consequently the heating effect due to inefficient pumping. In addition, work is known to be in progress to reduce the heat transfer to the burners by the use of insulation, so that an improvement over the values estimated here is possible. Another tendency, that of using fuel manifolds inside the combustion chamber, will have the opposite effect.

The use of ram air heat exchangers for fuel cooling is practicable with either system up to ram air temperatures of 60°C to 80°C i.e. up to Mach

numbers of 1.6 to 1.8 in the stratosphere. This method also appears to possess potentialities for coping with the cooling problem under fuel exhaustion conditions by operating a closed circuit through the heat exchangers and the equipment to be cooled.

The order in which the heat loads are absorbed by the fuel depends on the temperature to which cooling is required, the type of fuel system and its component temperature limitations and the method adopted for preventing excessive temperature rises during idling conditions.

For the case where this is accomplished by recirculation of excess fuel to the tank it appears desirable that the cabin, auxiliary equipment and aerodynamic heat loads should be absorbed by the fuel in the booster circuit before entry to the main pump in order to minimise the pumping heat load and because these are in general the applications in which the load may remain at a high level during engine idling conditions. The engine oil cooler would then be placed on the high pressure side of the fuel system.

When using a ram air heat exchanger to deal with idling conditions it will be necessary to absorb the auxiliary equipment and oil cooler heat loads in a high pressure region of the duplex system or in the spill circuit of a spill controlled system.

6 Conclusions

Examination of aircraft fuels and fuel systems indicates that when using kerosine at an initial temperature of 50°C, the fuel flow to a turbo-jet engine can be used to shield the fuel tank from aerodynamic heating and to cool the cabin air, the equipment, the engine lubricating oil and the fuel burners at speeds up to $M = 3$ or more and at altitudes up to more than 50,000 ft. These limits are dependent on preventing vapourisation in the fuel system and can only be defined exactly by detailed investigation into each individual system.

With volatile fuels such as wide cut gasoline, the present spill controlled burner system would be expected to give trouble due to vapourisation under the above conditions. In a duplex burner system the possibility of using this fuel as a coolant is marginal, being dependent on the temperature rise of the fuel in the burners, on which information is lacking.

An initial temperature of 50°C represents the worst case expected during operation in the tropics. In general the value will not be as high, thus giving the fuel system greater cooling capacity.

The low fuel pressures used in vapourising fuel systems at present precludes their employment for useful heat absorption, but there appears to be no reason why the pressure level should not be raised to that of either of the other two systems examined herein.

It is assumed that the fuel tanks are either insulated by about 1" of glass wool and shielded by the fuel flow or that, in the case where heat is allowed to flow into the tank, the initial fuel temperature is sufficiently low so that vapourisation is not caused as a consequence of aerodynamic heating. In the latter case, tank insulation can only be omitted if the period of high speed flight is very short, otherwise more extensive tank pressurisation or fuel precooling will be required.

Excessive fuel temperature rises at engine idling conditions are assumed to be prevented by some such means as recirculation to the tank or by the use of a ram air fuel cooler. A reheat pumping system should be arranged not to heat the fuel when reheat is inoperative.

At the assumed initial fuel temperature of 50°C, cooling of the cabin air and probably the electronic equipment can not be carried out directly by means of the fuel. Either colder fuel or a refrigeration cycle, possibly using the fuel as a heat sink, will be required for these applications.

7 Suggested action

Work is required to establish the maximum temperatures to which various fuels can be heated in representative fuel systems at high altitude cruise and idling conditions. In particular, information is required about the sensitivity of a duplex burner to vapourisation due to heat transfer in the combustion chamber.

The possibility of raising present day maximum temperatures by modification to the fuel system should be investigated.

Conservation of the cooling potential of the fuel is necessary and can be achieved by the use of insulation and by the reduction of waste heat from the pumping and auxiliary power systems. To this end, attention should be drawn to the necessity for efficient pumping, particularly at the main cruising condition. The average load efficiency of auxiliary power systems should be improved by designing them to have the minimum capacity to meet the demands made upon them.

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Attached:

Appendices I and II
Fig. No.1 to 24 SME 78026/R to SME 78049/R
Detachable Abstract Cards

Advance Distribution

DGTD(A)
PDSR(A)
PDQRD(A)
PD Eng RD
PD ARD - (Action)
DAQ
D Eng RD (1)
D Eng RD (2)
ADARD 1
AD Eng RD 1
TPA3/TIB - 150
Director NGTE
Director RAE
DDRAE(A)
DDRAE(E)
Structures Dept
Aero Dept
Pats 1/RAE

APPENDIX I

Heat input from the high pressure fuel pump

Engine driven plunger type pumps are in general use for the main fuel systems of turbo-jet engines, but other types, notably the centrifugal pump and other driving methods are also used for the reheat system. The simple gear pump has fallen into disfavour, but work is in progress at the moment to improve its characteristics. The efficiency of a plunger pump can be between 70% and 90% at maximum rate, decreasing at low rates to 25% to 50% dependent on the rate, pressure rise and speed. Actual values over a wide range are difficult to obtain, since the type test schedule does not call for efficiency or power measurements. Figs.4 and 5 illustrate the efficiency variation for a fixed stroke and a variable stroke plunger pump respectively, though the difference between the peak values shown may not necessarily be typical of each type. Efficiency values for centrifugal pumps are usually considerably lower. Fig.6[2] shows the characteristics of a centrifugal pump which appears to be representative of current designs for aircraft applications. Appreciably higher efficiencies than this can be realised by good design at higher flow rates and with pressurised inlets. Beeton[3] has obtained peak efficiencies of 60% under these conditions.

Fig.7 shows the temperature rise of the fuel during a single passage through a pump for any efficiency and pressure rise, the actual value in any system depending on the relation between flow and pressure rise demanded by the engine control system. This gives a complete picture of the heating effect of a variable displacement pump in which it should be possible to make the output equal the demand at all conditions. This is not the case for a fixed displacement pump since the flow through the latter is practically constant at a given speed; low fuel flows to the burners, i.e. at high altitude, are obtained by recirculating a large proportion of the pump throughput with a consequent increase in the rate of heat input.

The usual practice is to return this excess fuel to the pump inlet through a throttle. This results in a cumulative temperature rise greater in value than the sum of the temperature rises during each passage through the pump due to the degradation of the pressure energy of the fuel to heat during the throttling process. Fig.8 shows the temperature rise of the fuel in a pumping system for any flow ratio - defined as system output/pump output over the range 0 to 0.5.

The fuel flow range of an engine between sea level and high altitude maximum power is about 10:1 without taking into account the use of reheat, and assuming that the pump does not give any excess flow at sea level conditions. Fig.9 gives the temperature rise in various pumping systems at constant engine speed, and shows that for a fuel flow of 10% of the maximum available at that engine speed the temperature rise when using a constant displacement pump is about 21°C whereas those for the variable displacement and independently driven centrifugal pumps are 5°C and 18°C respectively. A directly driven centrifugal pump would operate more disadvantageously than any other in this respect. The pump pressure flow relationships imposed by the engine controller which are assumed in obtaining these curves are intended to represent practical operation at constant r.p.m.

The problem is aggravated by the provision of a reserve or reheat pump, because in these cases the output is reduced to zero for long periods, and if the pump is engine driven and is of the plunger or gear variety it is necessary to keep it from overheating by the passage of a certain quantity

of fresh fuel which must then be discharged back to the tank or otherwise disposed of. A reheat pump may pass up to 2½ times the main engine flow, and the extent of tank heating under those conditions depends on the power required to drive the pump when all the output is bypassed. For a fixed stroke plunger pump this value is unlikely to be less than a quarter of the power required when passing the maximum reheat fuel flow at 1,000 p.s.i. In the Sapphire Sa 6 installation in which the reheat pump capacity is equal to that of the main engine pump, the heat input to the fuel from the reheat pump alone at maximum continuous r.p.m. with reheat off is about 11 HP. Under these conditions at 55,000 ft the main engine pump alone operates below its limiting temperature when the fuel temperature in the tank is below about 50°C so that some of the reheat pump cooling flow can be passed through the main pump to the combustion chamber, thus reducing the tank heating effect. As the tank temperature increases however this can only be done to a progressively smaller extent. Typical tank temperature variations with time are given in Fig.10 which shows that operation for any length of time under these conditions is impracticable unless the fuel quantity is large or the temperature low.

If a centrifugal type pump with a separate bearing lubrication system is used, the problem may be eased by draining out the fuel and allowing it to run dry, but it is not believed practicable to employ this method with the other types. Another possible way of preventing fuel heating by the reheat pump is to have it driven independently of the engine by an electric motor or air turbine so that it can be stopped when not required. Both these methods are under consideration by the pump manufacturers.

Summarising the situation regarding heat input from the pumping system it is obvious that some of the methods used at present are designed without consideration being given to this effect, and are wasteful of the cooling potential of the fuel. The main engine fuel pumps are generally engine driven, and, if it is assumed that maximum thrust and high flight speeds will be used at sea level and hence that the sea level fuel consumption is very much greater than at altitude, the constant displacement variety of pump is seen to be unsuitable for this duty because its heating effect at high altitude maximum continuous conditions results in a loss of a considerable proportion of the cooling potential of the fuel. Variable displacement pumps are better for this duty, and even in this case the heating effect is appreciable since pump efficiency inevitably falls at low output. The artifice of sharing the pumping work at full output between two pumps may be worthwhile since one half of the installation may then be unloaded completely at low output with a consequent reduction in the overall heating effect, due to operation of one half at higher efficiency, coupled with the provision of reserve capacity which would give full load operation at high altitude in the event of failure of the other half.

For the reheat system the principal requirement is that there must be no fuel heating when reheat is inoperative. This would be best met by the use of independently driven pumps which can be stopped when not required. Presumably simplicity of the pump itself is desirable in this case, and gear or centrifugal types should be satisfactory if the reduced output required at high altitude can be accompanied by speed reduction.

APPENDIX II

Heat input from the oil cooler and spill burners

In earlier engines, the cooling of the turbine bearings and the associated parts was accomplished by compressor air bleed, but with increasing air temperatures the lubricating oil is now used for this purpose, a flood flow recirculating system being employed. The lubricating oil in turn is cooled by heat transfer to the high pressure fuel en route to the combustion chamber.

The heat input from this source depends on the operating conditions and the engine type. Some typical values are listed below, and Fig.11 shows the variation obtained over the operating range of an Olympus engine.

Operating condition	Single shaft engine			Two shaft engine		
	Make	Heat Input H.P.	Fuel temp rise °C	Make	Heat Input H.P.	Fuel temp rise °C
Sea level max. continuous	Sa 7 RA 14	16 12-17	5 5-7	BB 106 Olympus 100	35(design) 75	8 20
Sea level idling				"	11	37
50,000 ft max. continuous	RA14	5-12	10-23 (say 17)	"	18.5	35
50,000 ft idling				"	3.5	50

In the case of the Olympus engine the magnitude of the convective and radiant heat transfer to the burners appears to be approximately half that due to the oil cooler - see Fig.12. When using a spill controlled fuel system, a large proportion of the fuel passing through the burners is returned to the pump inlet at altitude conditions, and consequently this heating effect is cumulative. Consideration is being given to insulation of the burners in order to reduce this. The effect on systems other than that using spill control is not known.

In some aircraft the hydraulic oil is cooled by the fuel but no figures have been obtained for the magnitude of the consequent fuel heating.

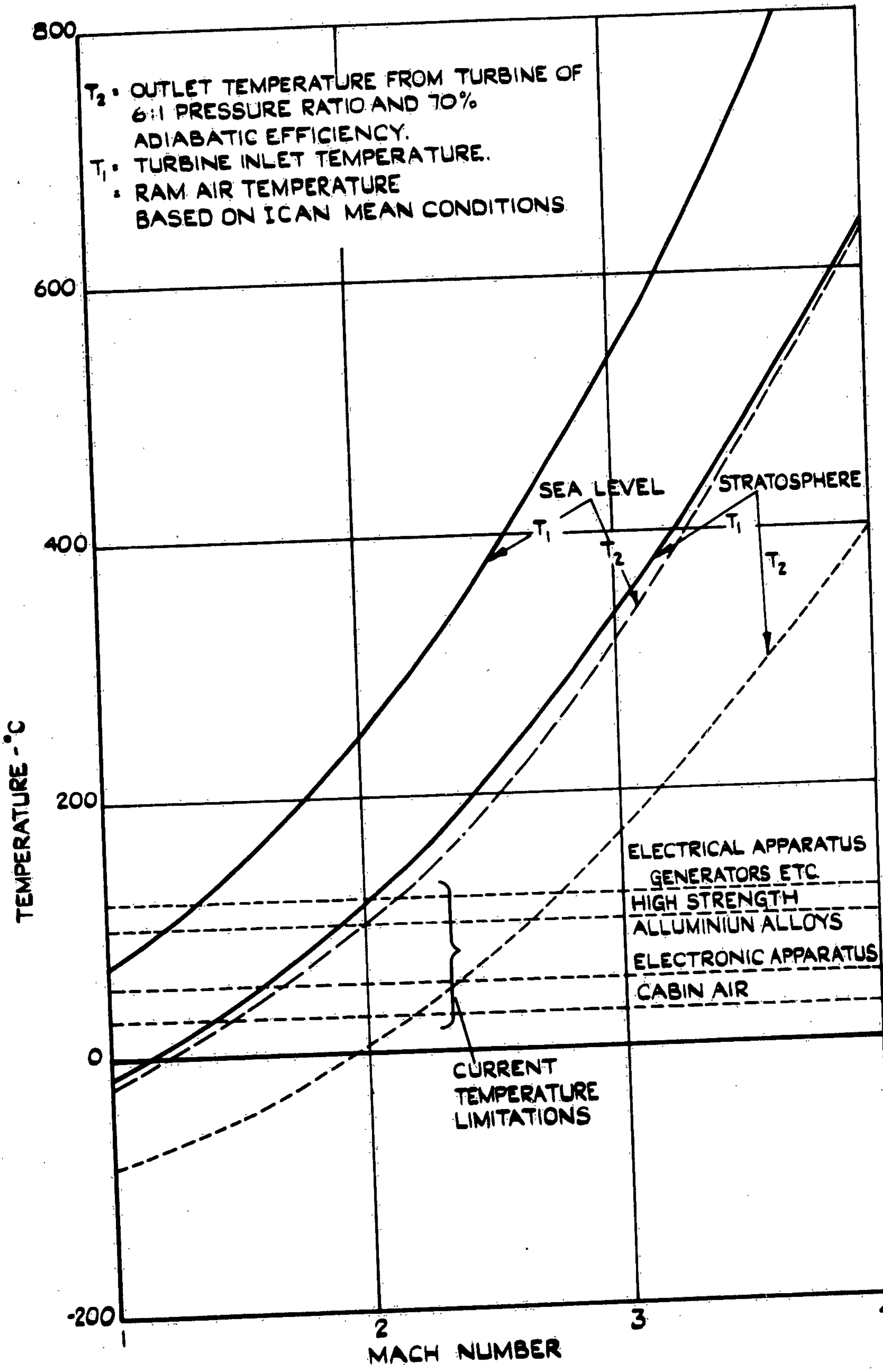


FIG. I. LIMITATIONS OF SIMPLE AIR COOLING METHODS.

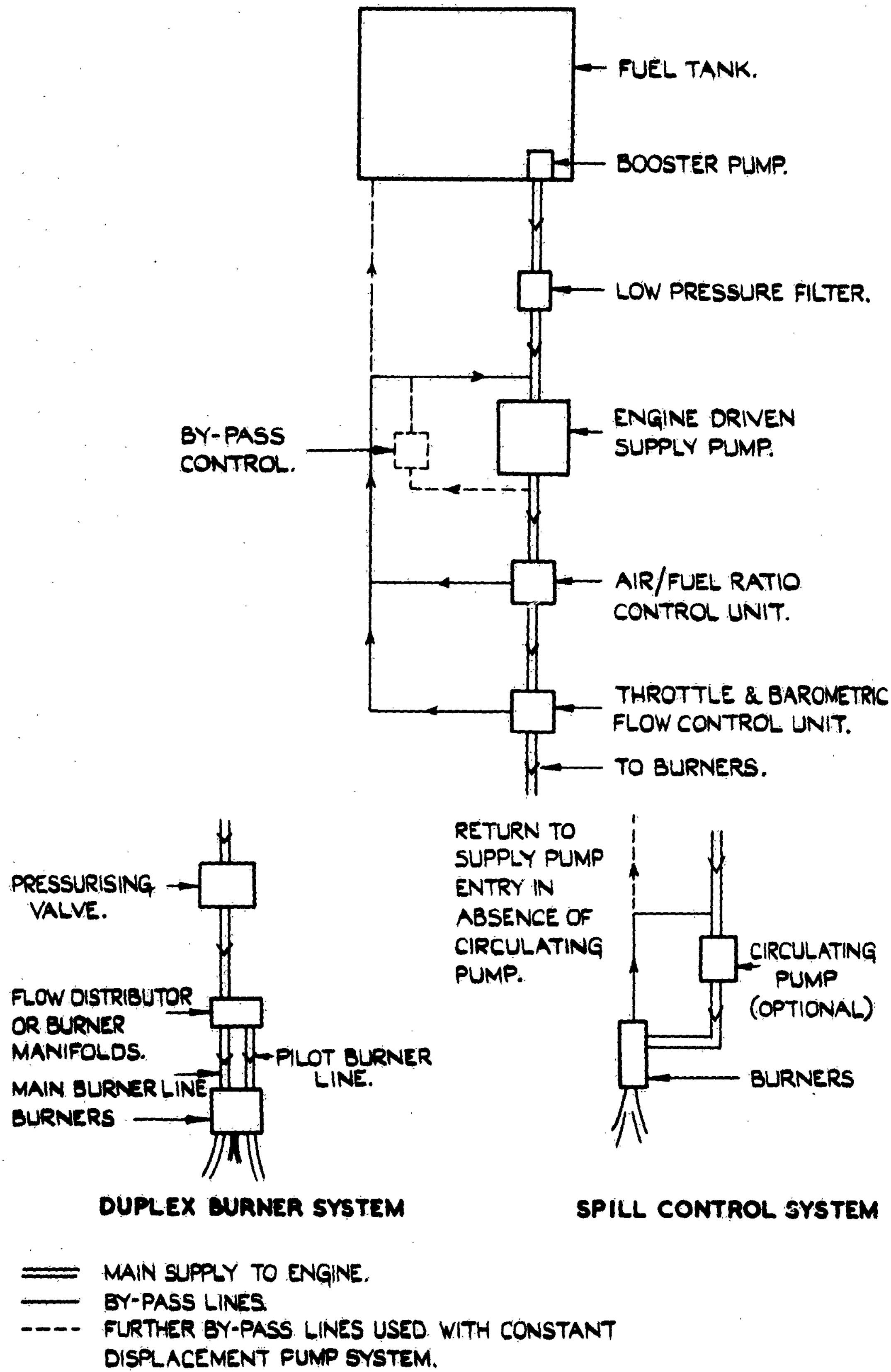


FIG. 2. OUTLINE OF MAIN COMPONENTS OF TWO TYPICAL TURBO-JET ENGINE FUEL SYSTEMS.

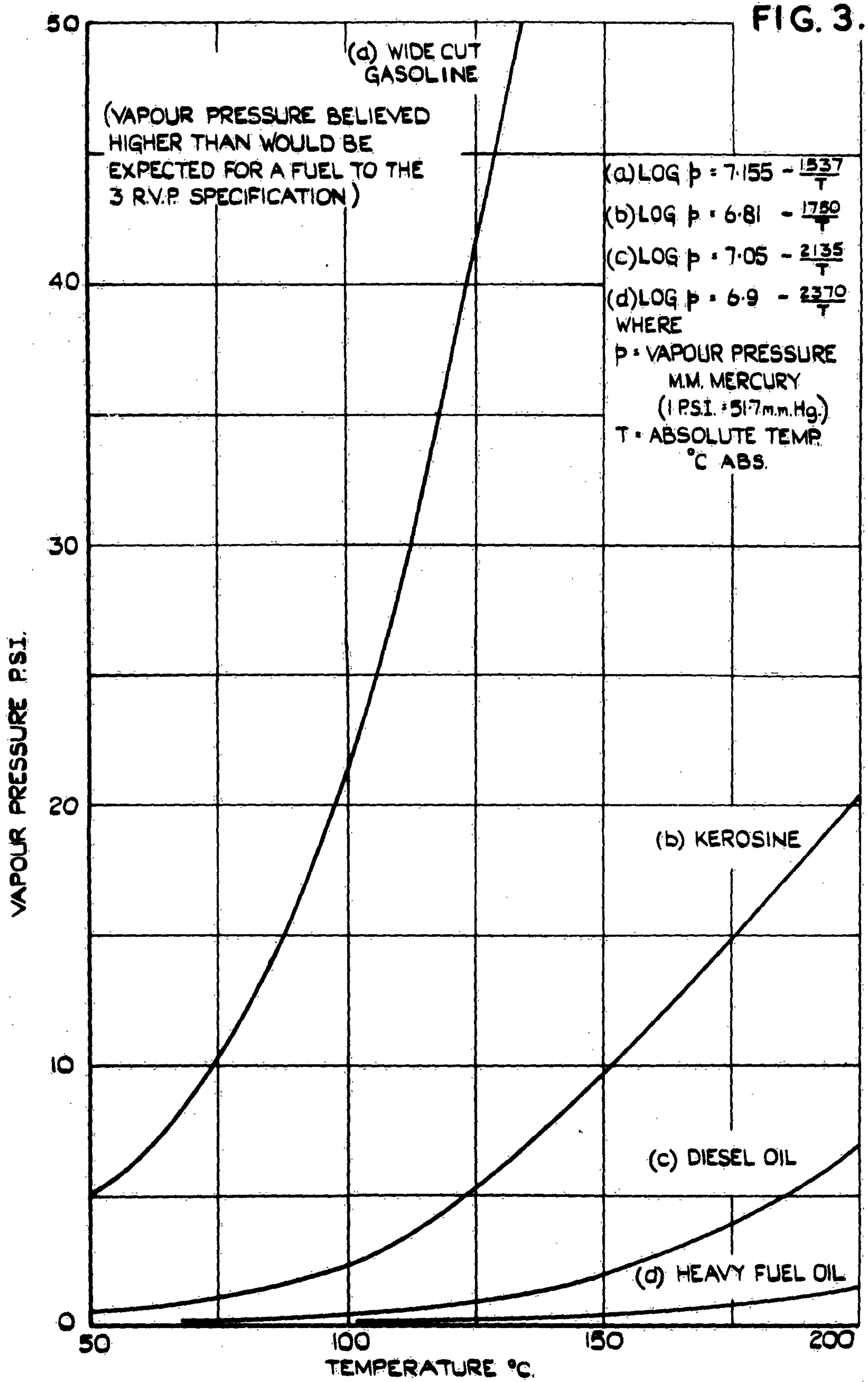


FIG. 3. THE VARIATION OF FUEL VAPOUR PRESSURE WITH TEMPERATURE.

FIG. 4.

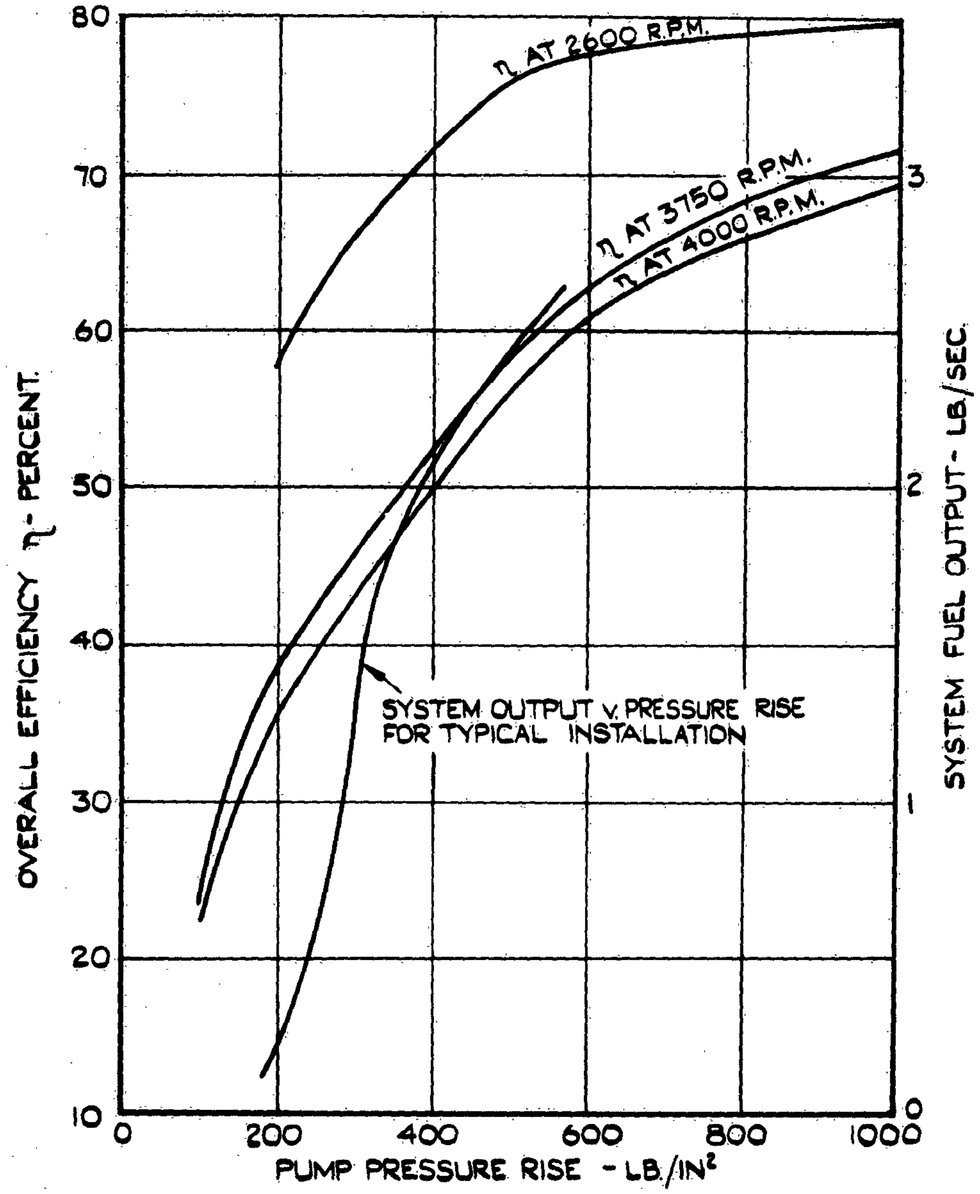


FIG. 4. OVERALL EFFICIENCY CHARACTERISTIC OF A FIXED-STROKE PLUNGER FUEL PUMP.

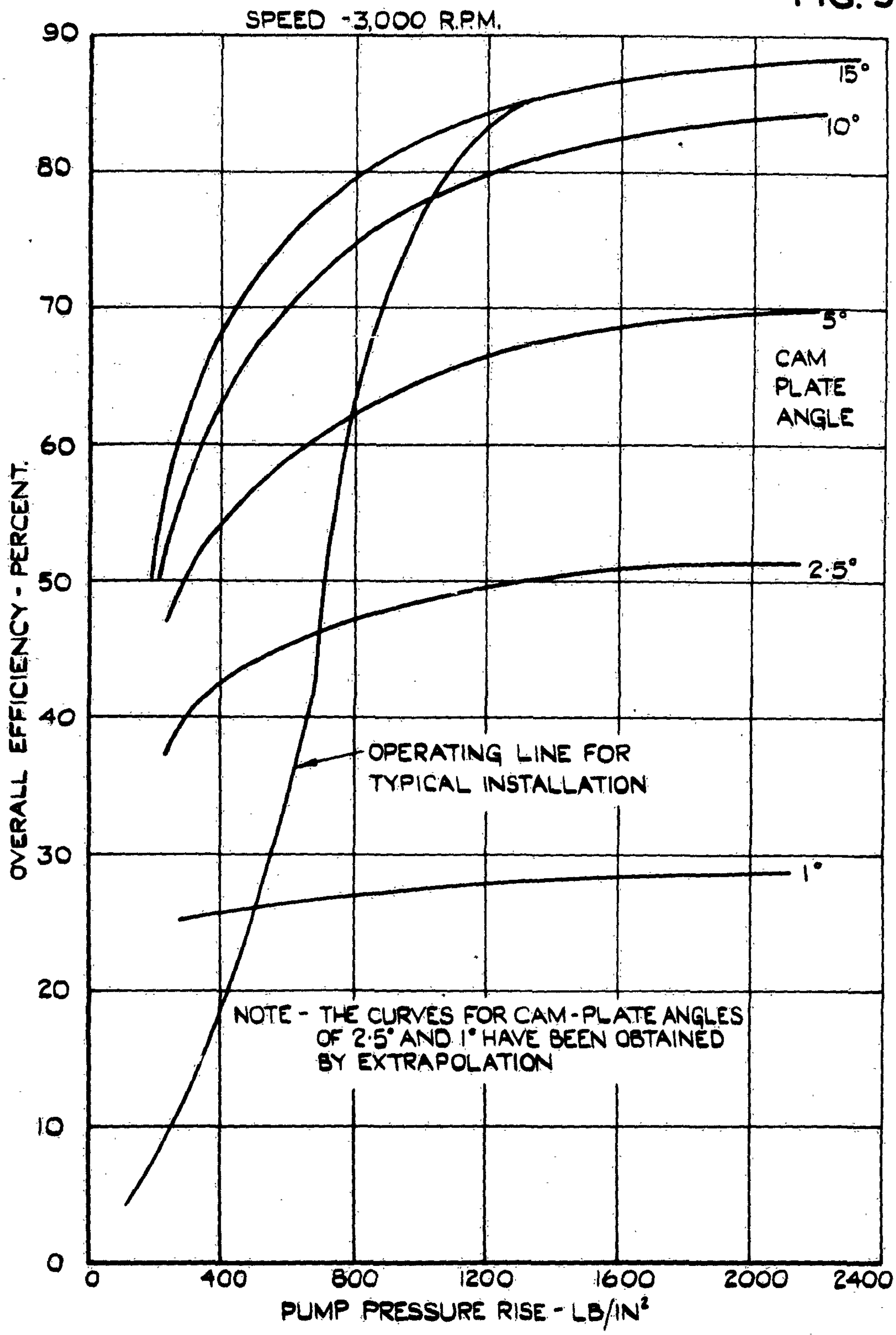


FIG. 5. OVERALL EFFICIENCY CHARACTERISTIC OF A VARIABLE-STROKE PLUNGER FUEL PUMP.

FIG. 6.

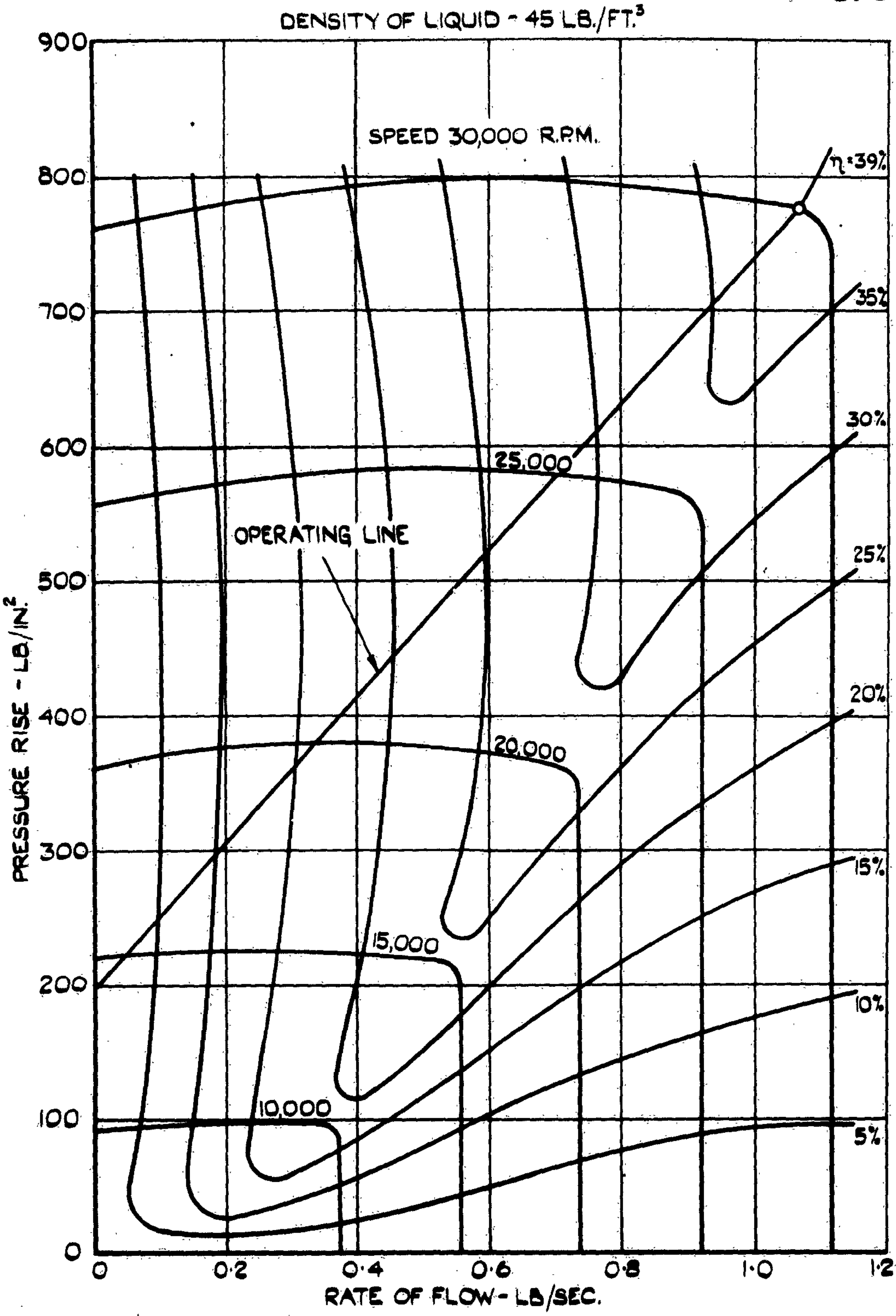


FIG. 6. CHARACTERISTICS OF A TYPICAL CENTRIFUGAL FUEL PUMP.

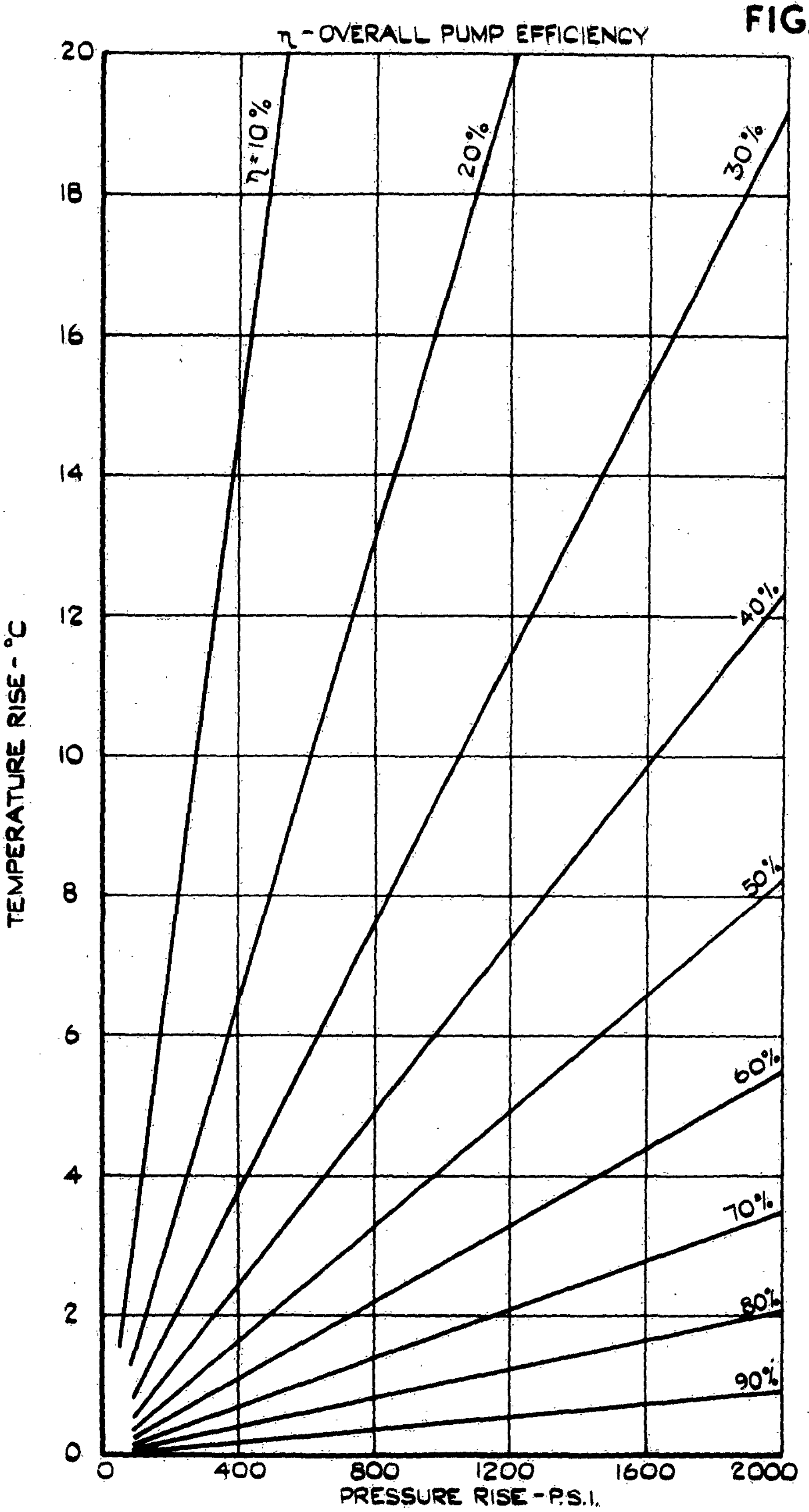


FIG.7. FUEL TEMPERATURE RISE WITH VARYING PRESSURE RISE AND PUMP EFFICIENCY – NO BY-PASS.

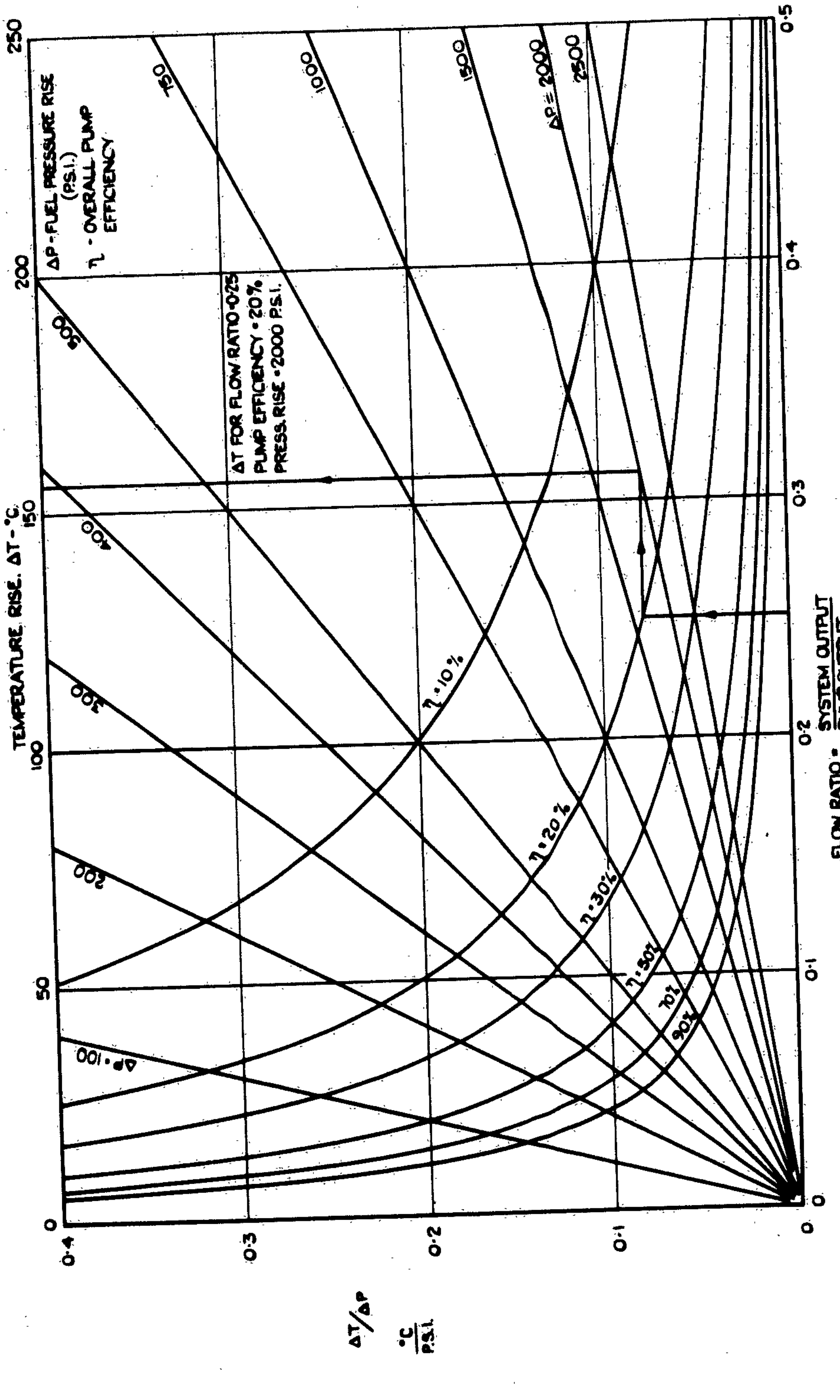


FIG. 8. FUEL TEMPERATURE RISE WITH VARYING BYPASS TO PUMP INLET.

THE PUMP DESIGN CONDITIONS AND THE PUMP PRESSURE-FLOW RELATIONSHIPS IMPOSED BY THE CONTROLLER ARE INTENDED TO REPRESENT AIRCRAFT CONSTANT R.P.M. OPERATING CONDITIONS AS FOLLOWS :-

	TYPE OF PUMP	FIXED-STROKE	VARIABLE-STROKE	CENTRIFUGAL
MAX. CONDITIONS	R.P.M.	3,750	3,000	30,000
	PRESSURE (P.S.I.)	555	1,300	775
	η	·608	·851	·39
	ENGINE DRIVEN	YES	YES	INDEPENDENTLY DRIVEN
PART FLOW	PRESSURE-FLOW RELATIONSHIP	AS ON FIG. 3.	AS ON FIG. 4.	AS ON FIG. 5.
	BYPASS TO PUMP INLET	YES	NO	NO

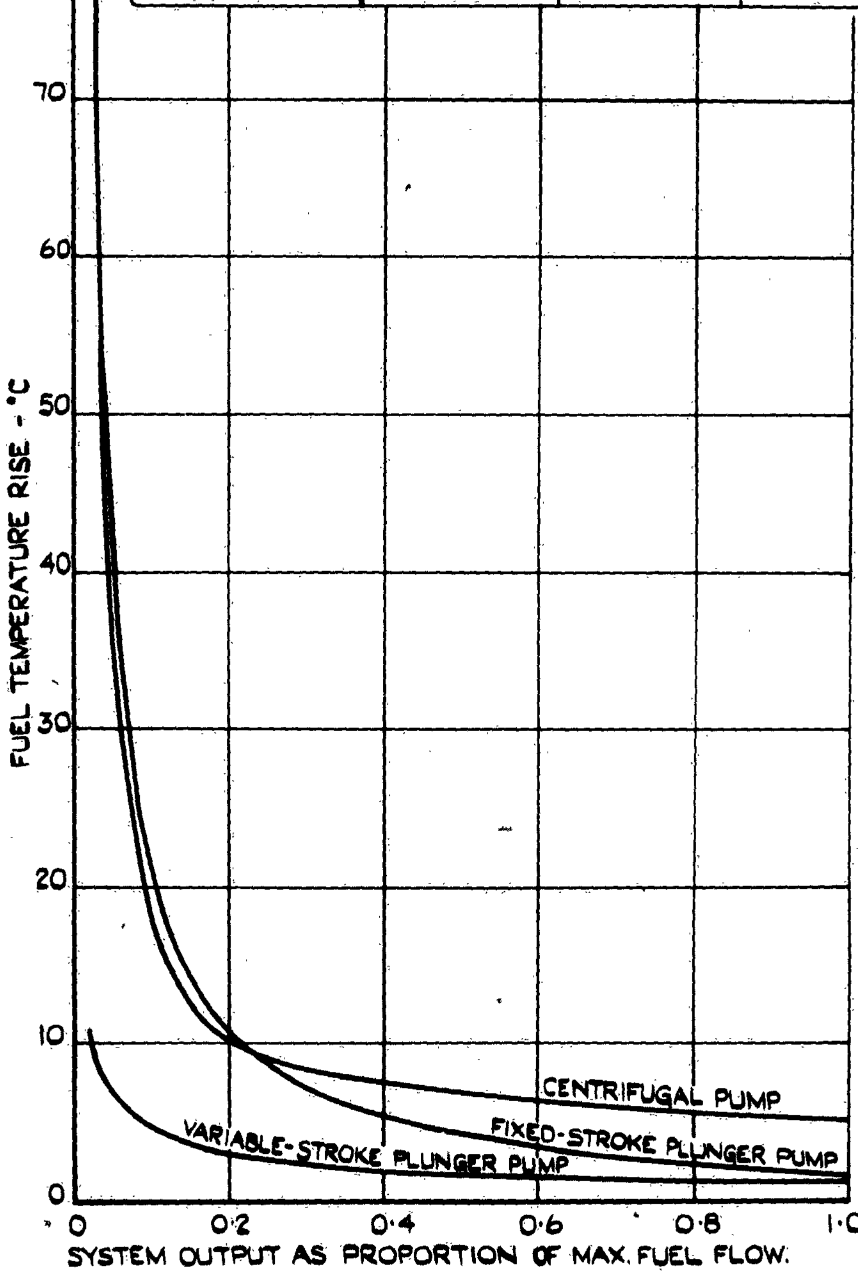


FIG. 9. TEMPERATURE RISE IN VARIOUS PUMPING SYSTEMS AT CONSTANT ENGINE R.P.M.

FIG. 10.

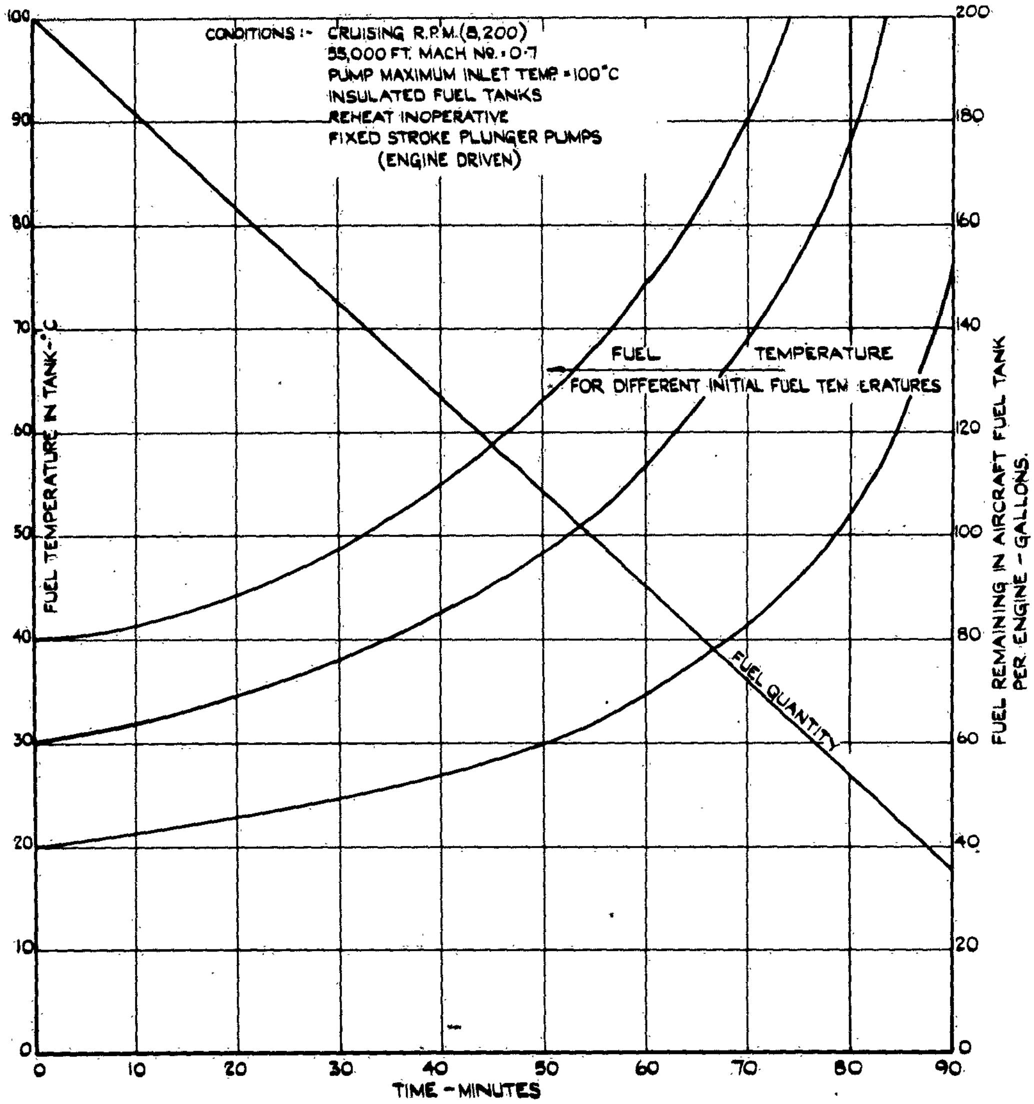


FIG. 10. EFFECT OF BLEEDING FUEL BACK TO INSULATED TANK IN FUEL SYSTEM OF SAPPHIRE ENGINE WITH REHEAT PUMP.

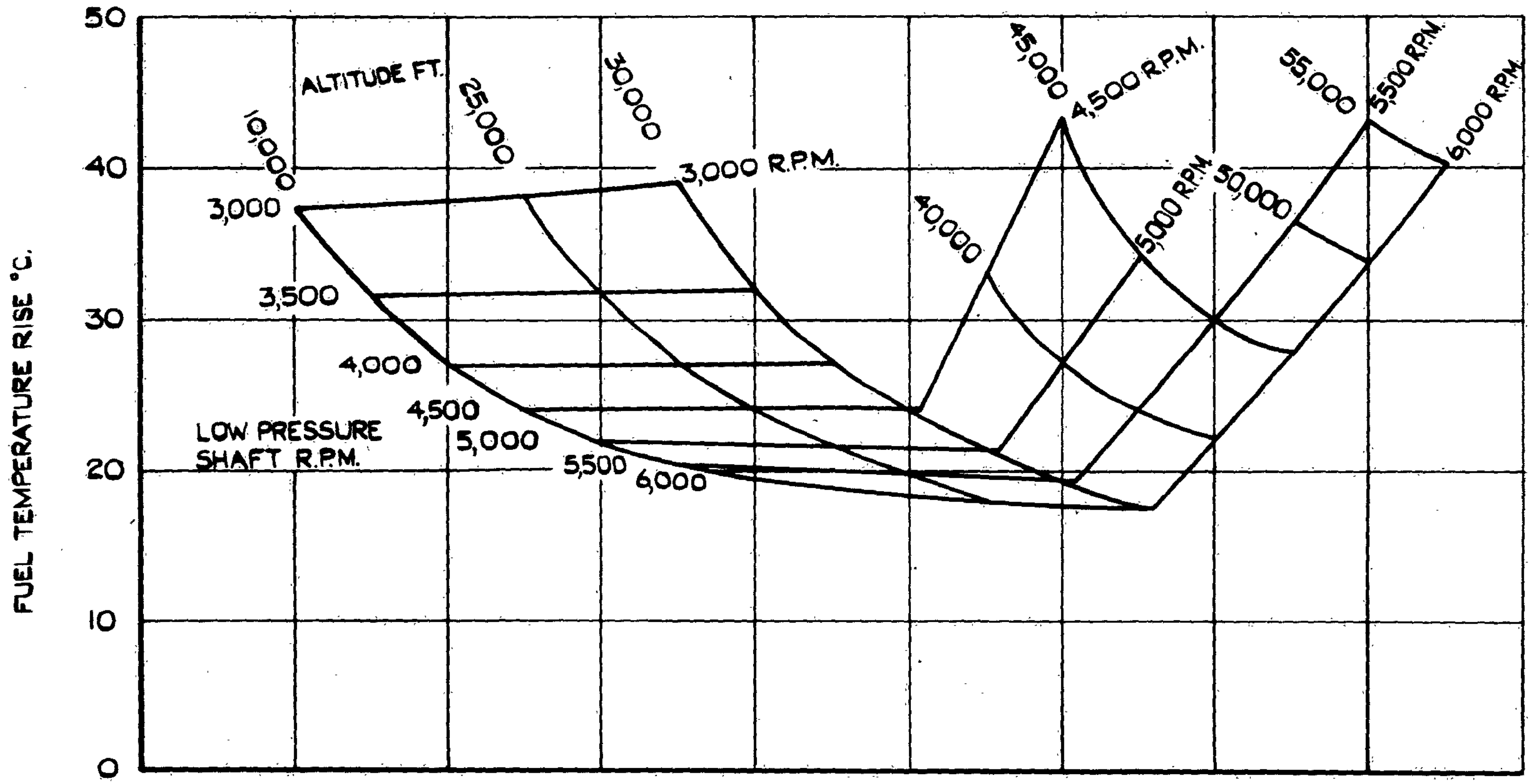


FIG. 11. FUEL HEATING IN OLYMPUS 100 OIL COOLER, (FLIGHT MACH Nº. 0·76)

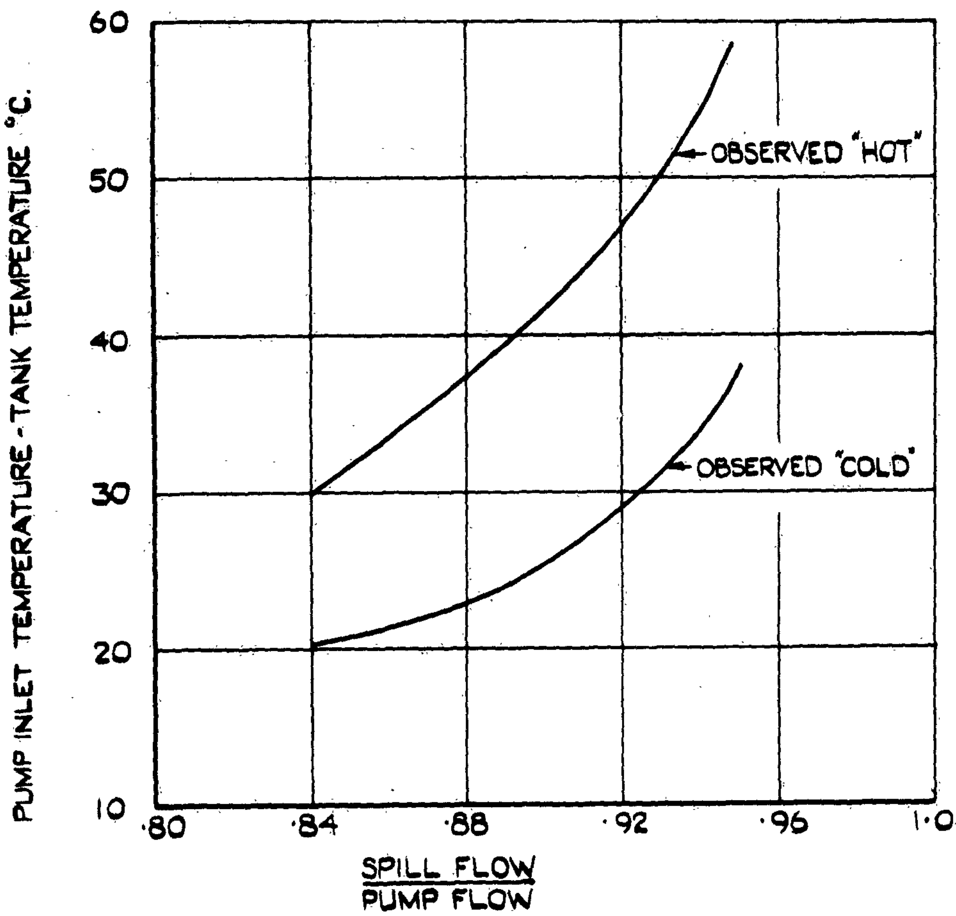
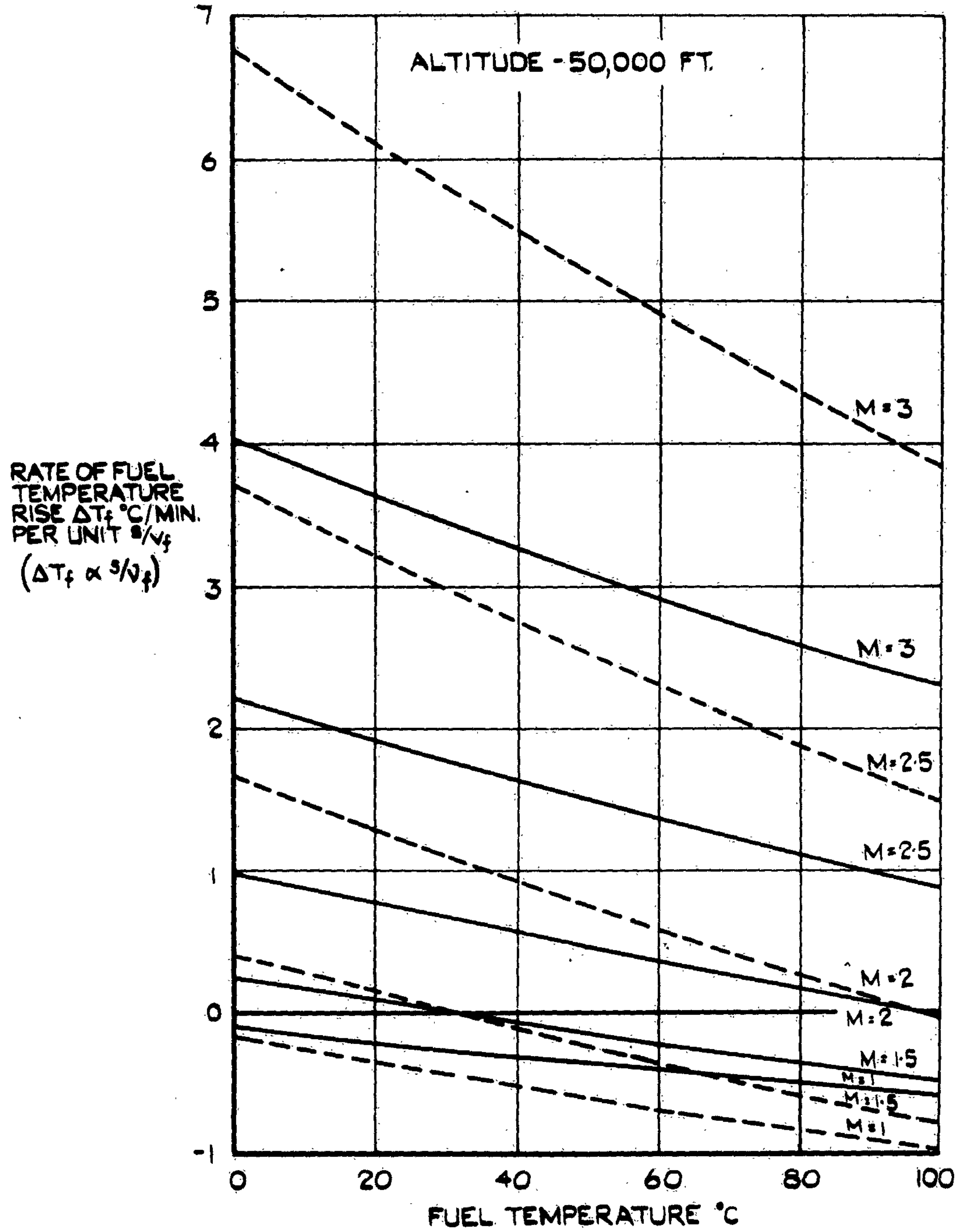


FIG. 12. FUEL HEATING IN A SPILL CONTROLLED FUEL SYSTEM.



S - TANK SURFACE AREA THROUGH WHICH HEAT TRANSFER TAKES PLACE - FT^2

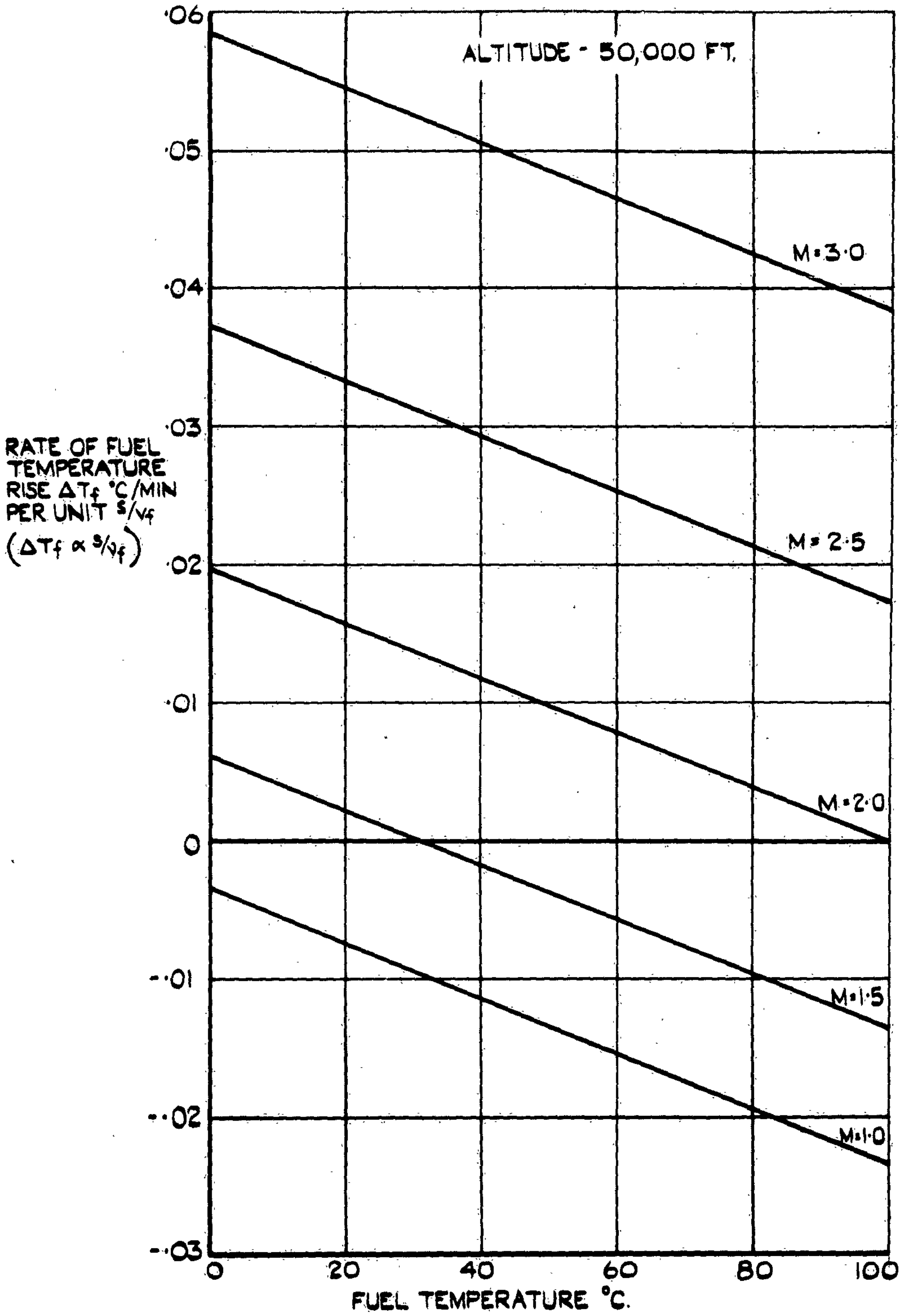
V_f - FUEL VOLUME - FT^3

--- TANK CENTRE AT 3 FT. FROM LEADING EDGE, REPRESENTATIVE OF WING TANK

— TANK CENTRE AT 40 FT. FROM AIRCRAFT NOSE, REPRESENTATIVE OF FUSELAGE TANK.

FIG. 13. RATE OF FUEL TEMPERATURE RISE IN UNINSULATED TANKS AT VARIOUS MACH NUMBERS.

FIG. 14.



S - TANK SURFACE AREA THROUGH WHICH HEAT TRANSFER TAKES PLACE - FT^2

V_f - FUEL VOLUME - FT^3

FIG. 14. RATE OF FUEL TEMPERATURE RISE IN INSULATED TANKS AT VARIOUS MACH Nos.

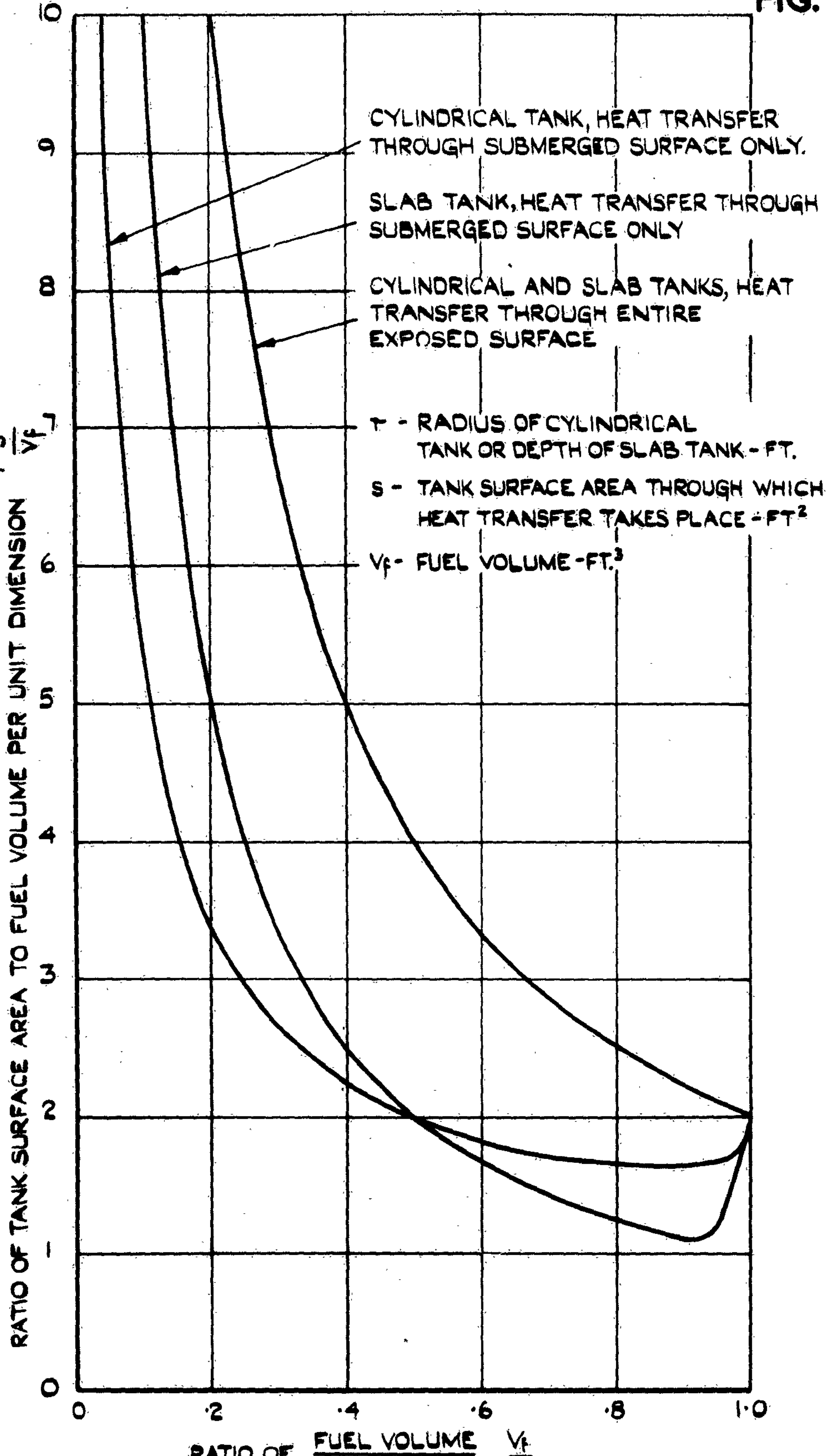
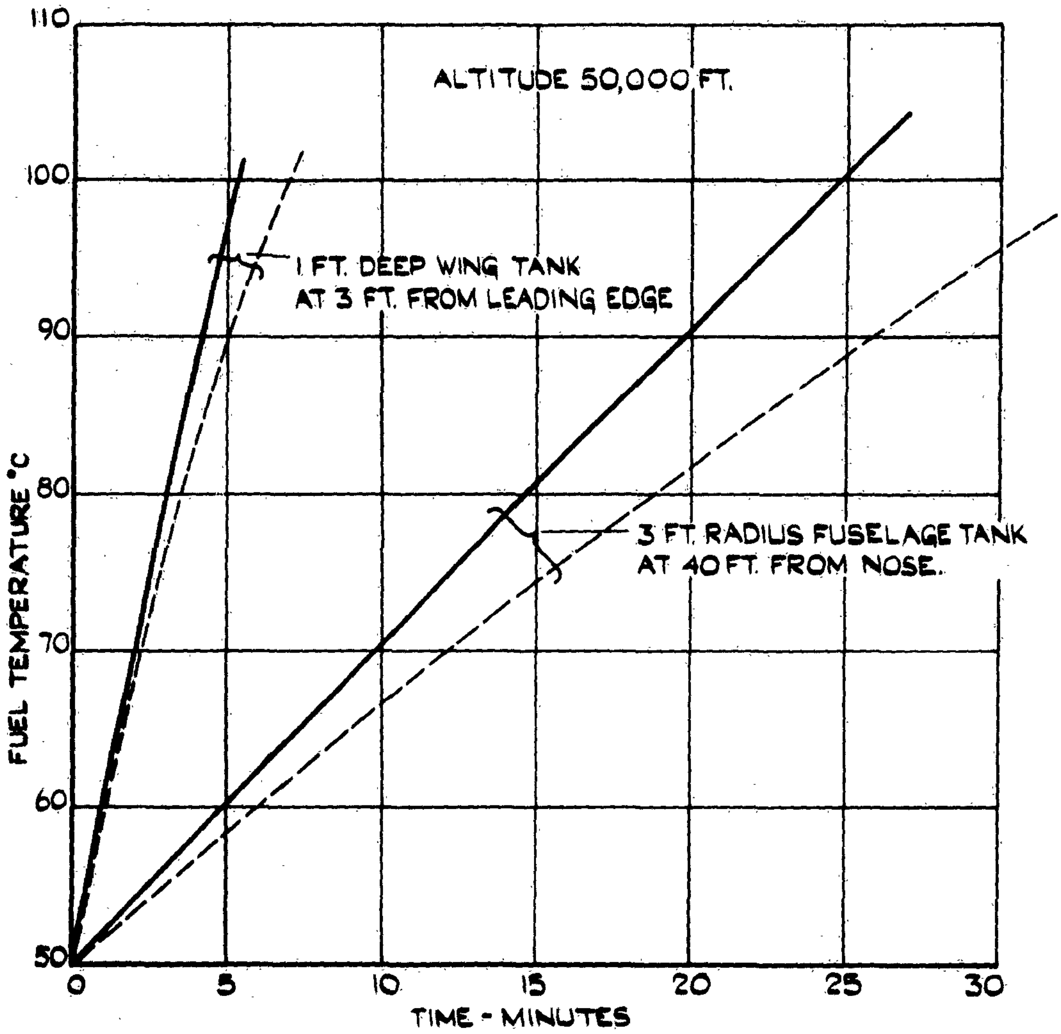


FIG. 15. RATIO OF SURFACE AREA FOR HEAT TRANSFER/FUEL VOLUME FOR FUEL TANKS WITH VARYING CONTENTS.

(NOT INCLUDING ENDS OF CYLINDRICAL TANKS OR SIDES OF SLAB TANKS)



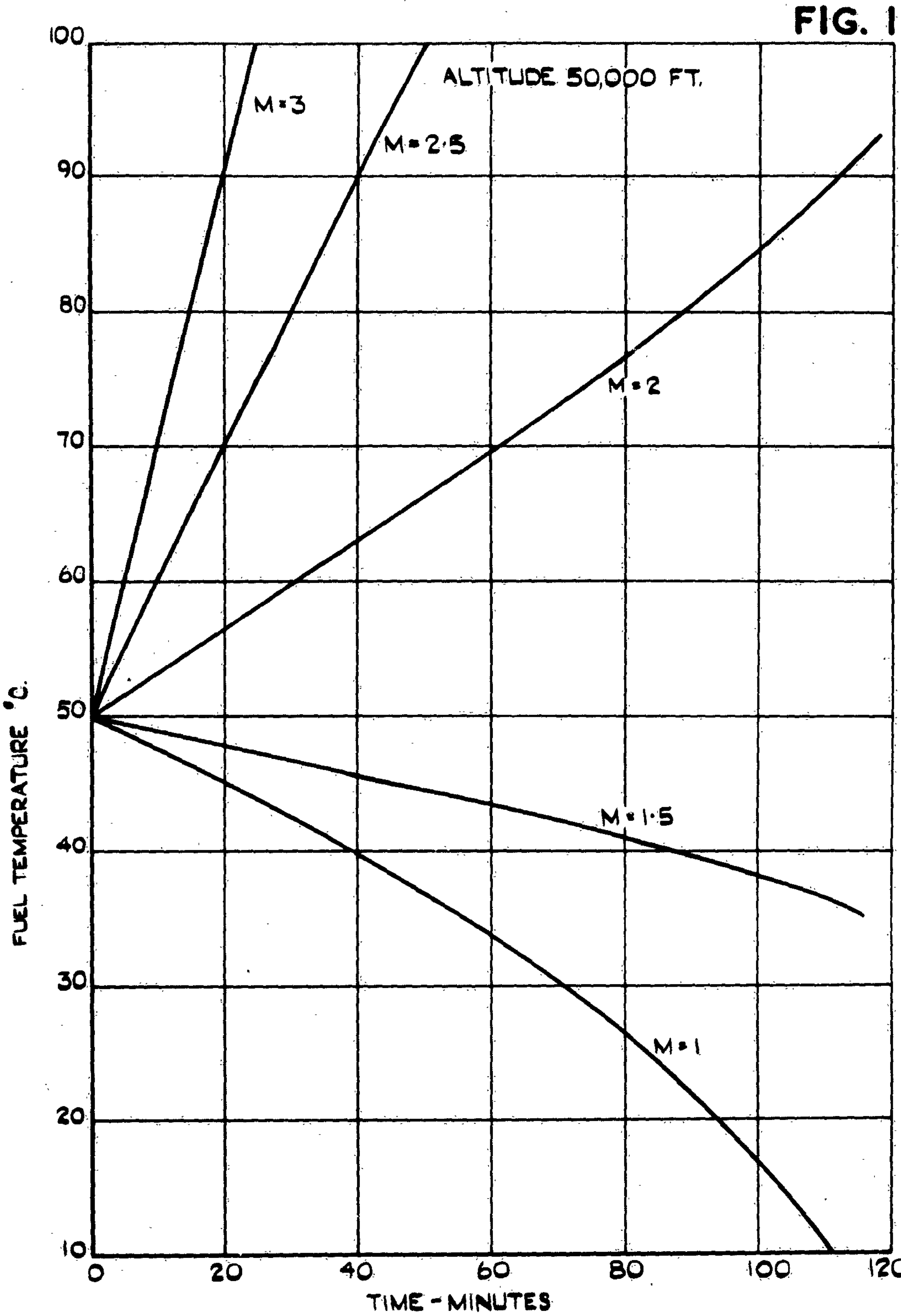
TANKS ASSUMED TO BE EMPTIED AT A STEADY RATE IN 2 HOURS.
HEAT TRANSFER ASSUMED NEGLIGIBLE THROUGH ENDS OF FUSELAGE TANK OR SIDES OF A WING TANK.

—— HEAT TRANSFER THROUGH ENTIRE EXPOSED SURFACE.

--- HEAT TRANSFER THROUGH SUBMERGED SURFACE ONLY.

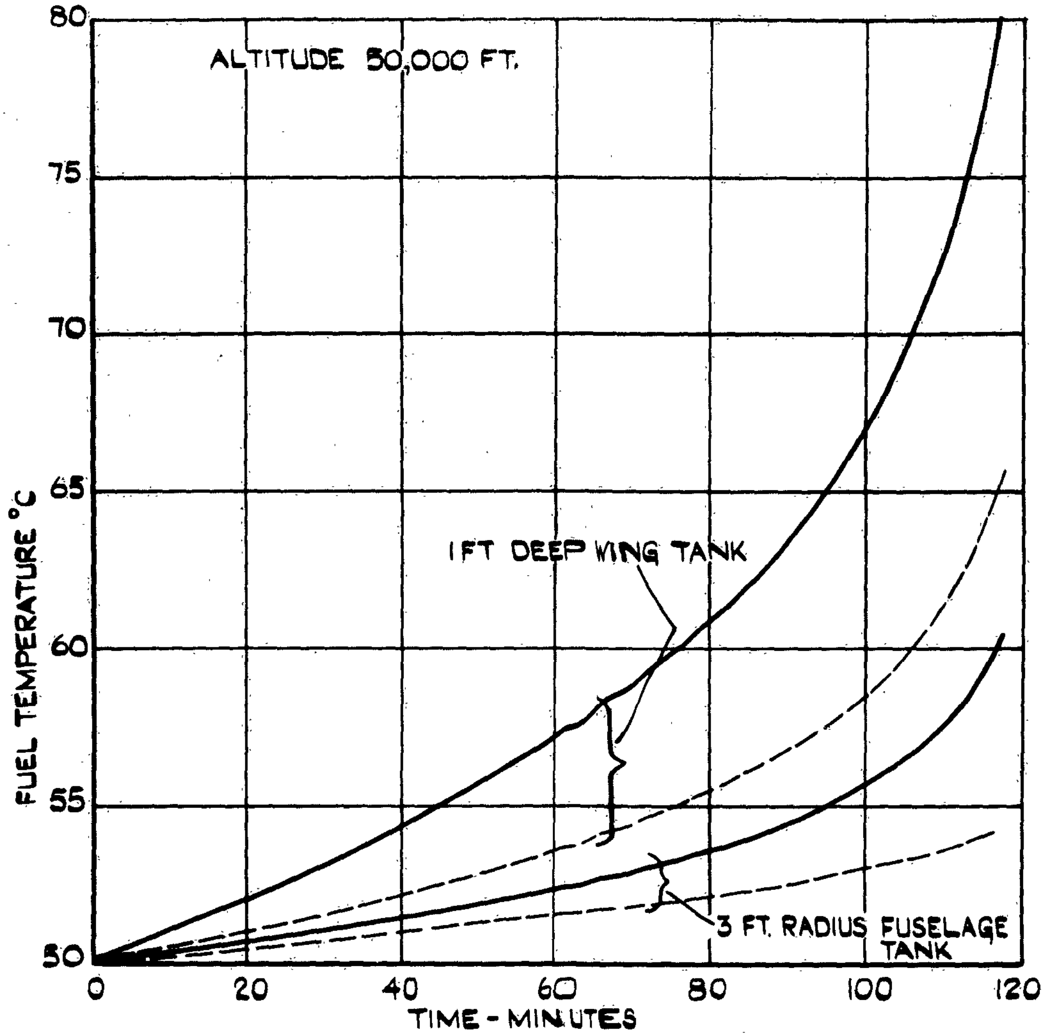
FIG. 16. FUEL TEMPERATURE RISE IN UNINSULATED TANKS AT M = 3.

FIG. 17.



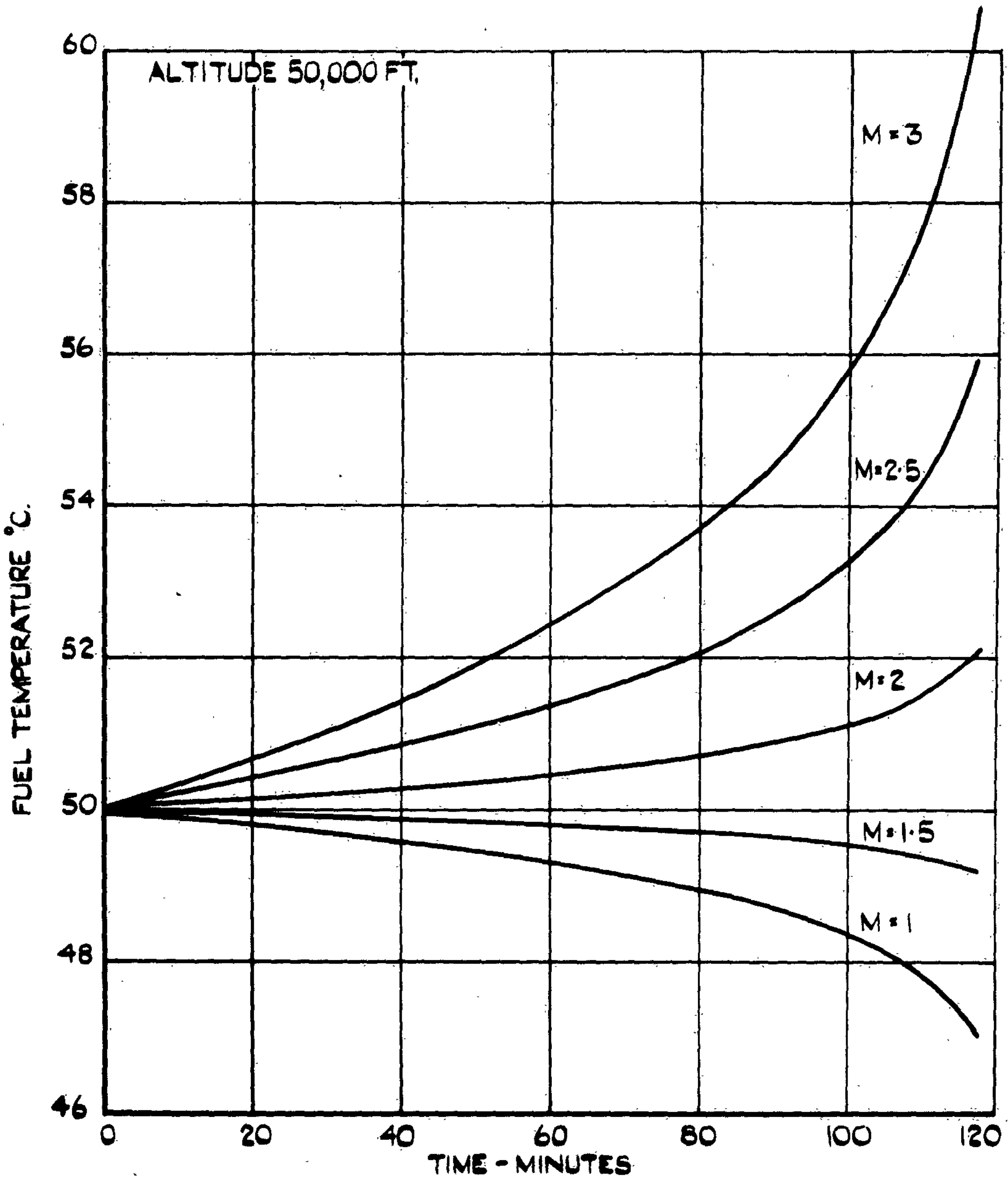
3 FT. RADIUS TANK AT 40 FT. FROM THE AIRCRAFT NOSE.
ASSUMED TO BE EMPTIED AT A STEADY RATE IN 2 HOURS.
HEAT TRANSFER THROUGH THE ENTIRE EXPOSED SURFACE WITH NEGLIGIBLE TRANSFER FROM THE TANK ENDS.

FIG. 17. FUEL TEMPERATURE RISE IN UNINSULATED FUSELAGE TANK AT VARIOUS MACH NUMBERS.



TANKS ASSUMED TO BE EMPTIED AT A STEADY RATE IN 2 HOURS.
HEAT TRANSFER ASSUMED NEGLIGIBLE THROUGH ENDS OF FUSELAGE TANK OR SIDE OF A WING TANK.
—— HEAT TRANSFER THROUGH ENTIRE EXPOSED SURFACE.
--- HEAT TRANSFER THROUGH SUBMERGED SURFACE ONLY.

FIG. 18. FUEL TEMPERATURE RISE IN INSULATED TANKS AT M=3.



3 FT. RADIUS TANK ASSUMED TO BE EMPTIED AT A STEADY RATE IN 2 HOURS. HEAT TRANSFER THROUGH ENTIRE EXPOSED SURFACE WITH NEGLIGIBLE TRANSFER FROM TANK ENDS.

FIG. 19. FUEL TEMPERATURE RISE IN INSULATED FUSELAGE TANK AT VARIOUS MACH NUMBERS.

FIG. 20 (a & b)

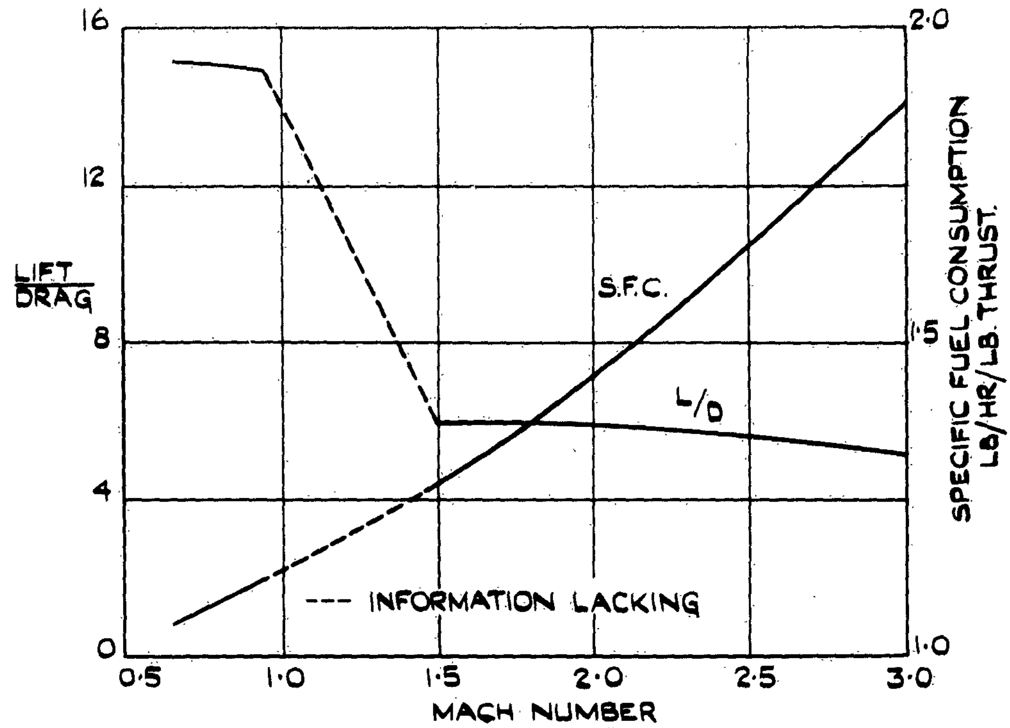


FIG. 20 (a) AIRCRAFT $\frac{\text{LIFT}}{\text{DRAG}}$ AND ENGINE SPECIFIC FUEL CONSUMPTION v MACH No.

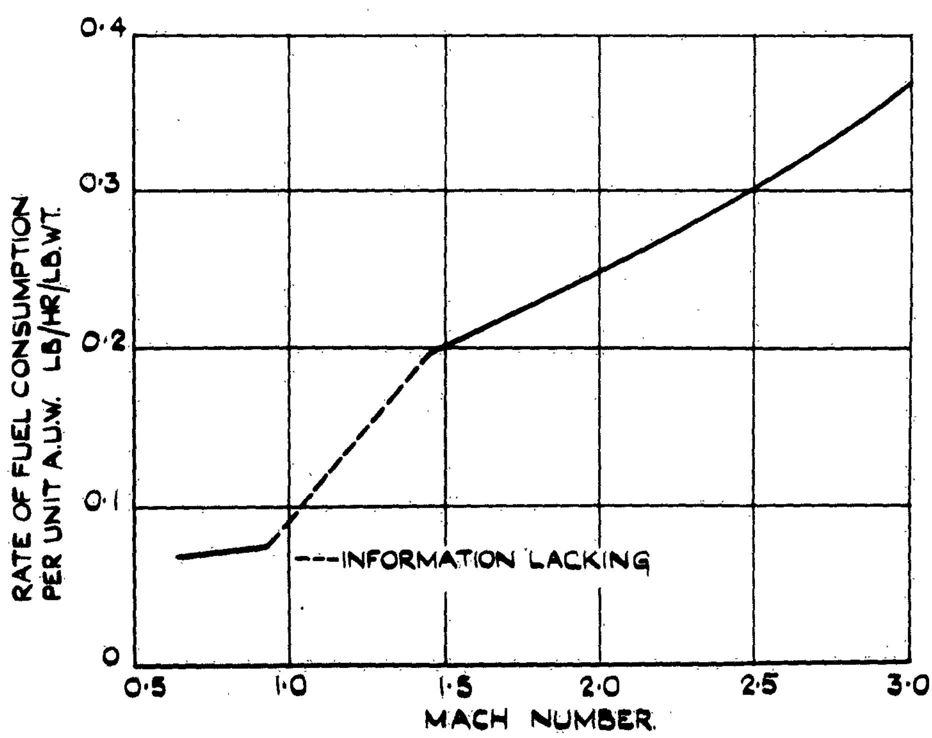


FIG. 20 (b) RATE OF AIRCRAFT FUEL CONSUMPTION PER UNIT A.U.W. v MACH No.

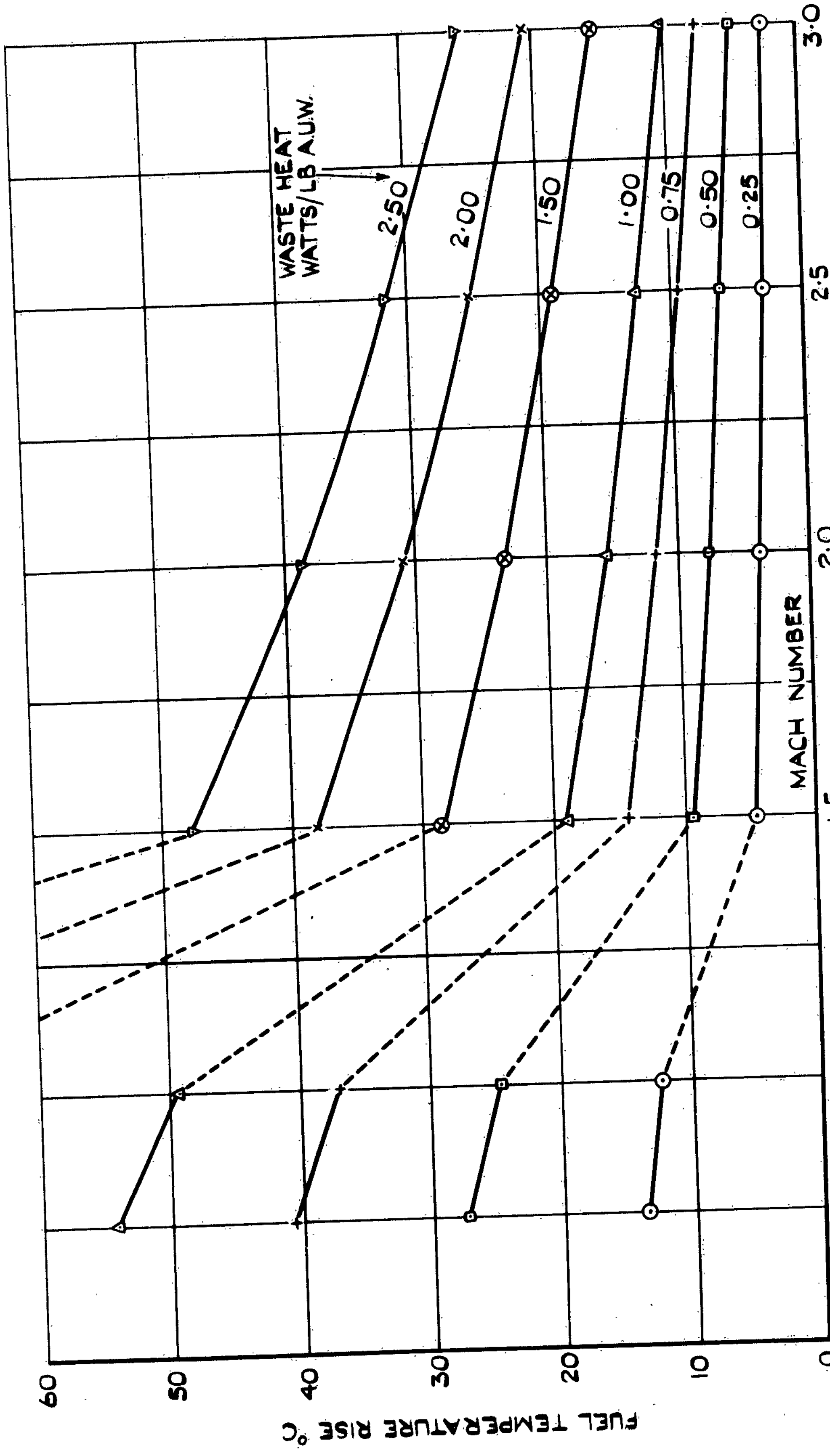


FIG. 21. FUEL TEMPERATURE RISE DUE TO ABSORBING WASTE HEAT FROM THE EQUIPMENT.

FIG. 22.

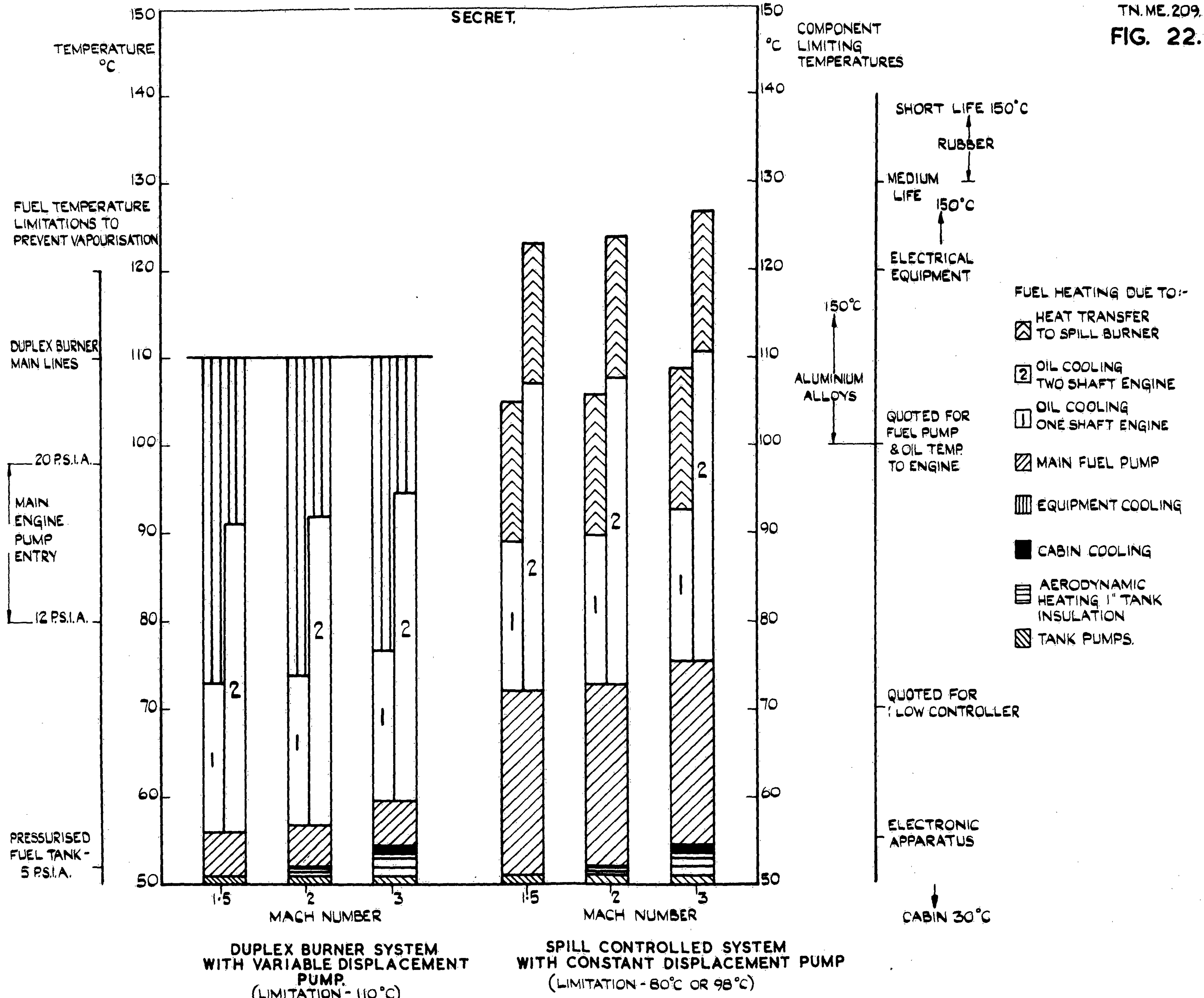


FIG. 22. HEATING OF THE FUEL FLOWING TO THE ENGINES IN HIGH SPEED AIRCRAFT.
(CRUISE AT 50,000 FT., INITIAL FUEL TEMPERATURE 50°C, FUEL VAPOURISATION LIMITS QUOTED FOR WIDE CUT GASOLINE, SEE TABLE 2 FOR LIMITS APPROPRIATE TO OTHER FUELS)

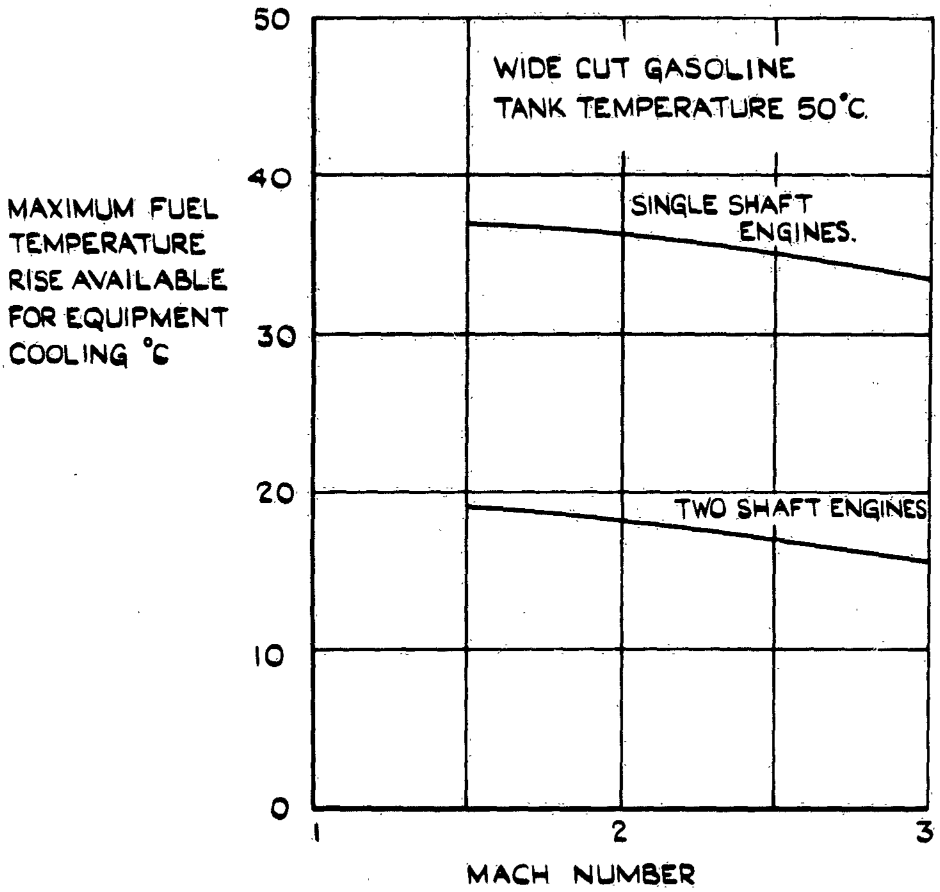
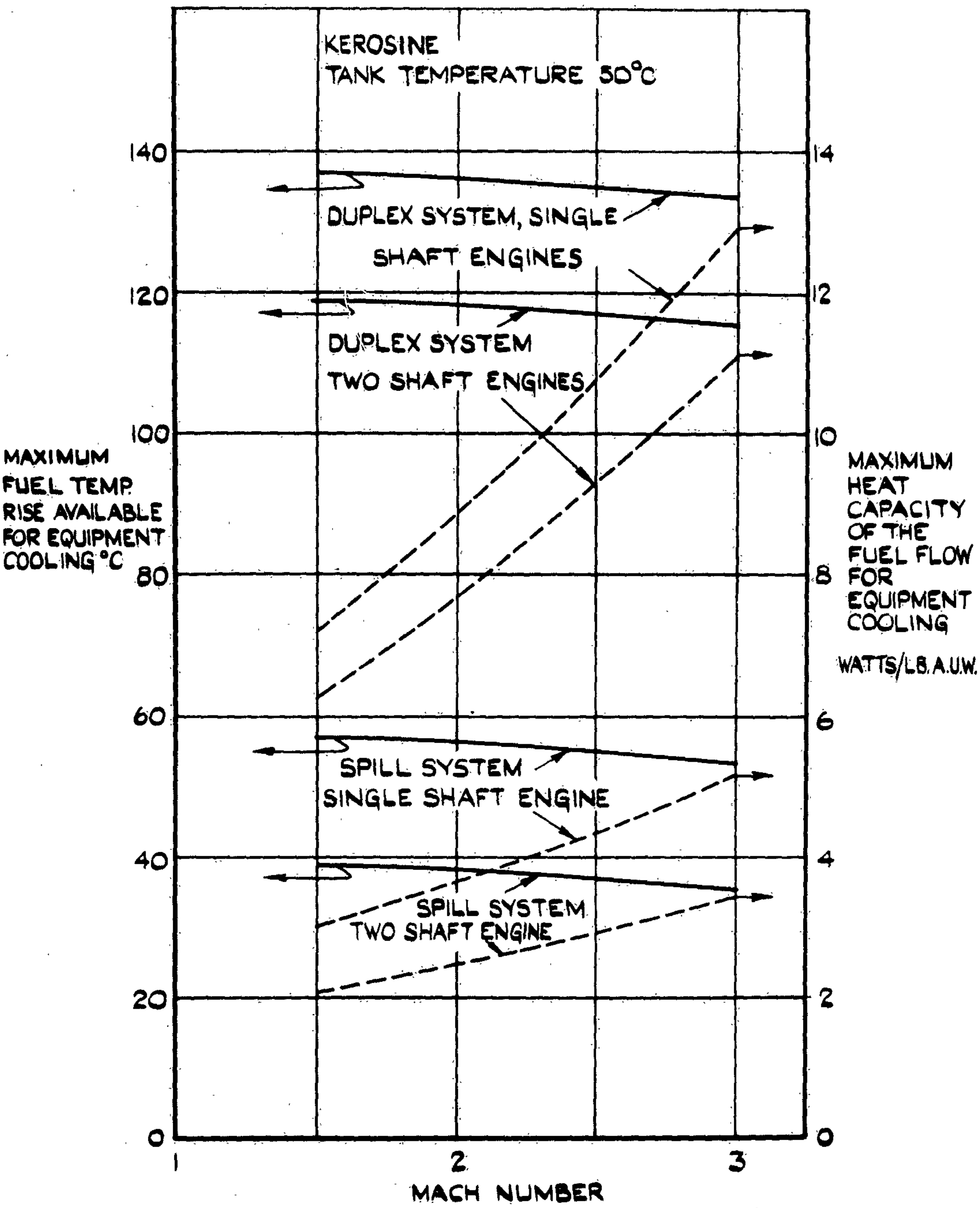


FIG. 23. MAXIMUM FUEL TEMPERATURE RISE FOR EQUIPMENT COOLING.

(CRUISE AT 50,000 FT., DUPLEX BURNER SYSTEM. THIS WILL BE REDUCED BY FUEL TEMPERATURE RISE IN THE BURNERS)



NOTE: RAISING THE BOOSTER PRESSURE FROM THE 12 P.S.I.A. VALUE ASSUMED HERE TO 20 P.S.I.A. WILL PRACTICALLY DOUBLE THE HEAT CAPACITY OF THE SPILL SYSTEM. THE DUPLEX SYSTEM VALUES WILL BE REDUCED BY HEAT TRANSFER TO THE BURNERS.

FIG. 24. ABSORPTION OF THE WASTE HEAT FROM THE AIRCRAFT EQUIPMENT BY THE FUEL FLOWING TO THE ENGINES.

(CRUISE AT 50,000 FT. DUPLEX AND SPILL BURNER SYSTEMS)

[dstl]

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AD#: AD0091861

Date of Search: 19 November 2009

Record Summary: DSIR 23/24486
Title: Use of Fuel for Cooling Purposes in Aircraft
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department): ARC 18649
Held by: The National Archives, Kew

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